Research Article

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Identification of active meteorological systems in Santa Catarina with potential socioeconomic impact

Abstract

The article aims to comprehensively identify and analyze the meteorological systems operating in the State of Santa Catarina, Brazil, shedding light on their characteristics, scales of action, and associated impacts, particularly regarding socioeconomic impacts on society. Utilizing a bibliographic review, the study synthesizes knowledge about these systems, including their characteristics and scales. A total of 62 manuscripts were analyzed, revealing the complexity of climatic phenomena from interdecadal scales to mesoscales. It covers the Pacific Decadal Oscillation and El Niño, the Madden-Julian Oscillation, and the Antarctic Oscillation (Southern Annular Mode - SAM), cyclones, the South Atlantic Convergence Zone (SACZ), the South Atlantic Subtropical Anticyclone (South Atlantic High - SAH) and the South Pacific Subtropical Anticyclone (South Pacific High - SPH), Upper Tropospheric Cyclonic Vortex (UTCV), Weather Systems, and Jet Streams (both Upper-Level and Low-Level Jets), Mesoscale Convective Complexes, and Squall Lines. Although microscale phenomena were not specifically identified in the research, they represent a highly active scale of meteorological phenomena essential for understanding the fine interactions that affect the local climate, highlighting the impact of geographical characteristics and specific microclimatic variations in Santa Catarina. Integrating these scales of analysis and identifying the active systems in the State can contribute to the needs of various segments, especially those employing a holistic approach in meteorology, aiming for a better understanding and prediction of meteorological systems.

Keywords: meteorology, Santa Catarina, climate adaptation, climate change, climate impact in Santa Catarina

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Abbreviations: ABL, atmospheric boundary layer; BHS, Bolivian high system; Cb, cumulonimbus; ENSO, El Niño southern oscillation; ITCZ, intertropical convergence zone; LLJs, low level jets; MCZ, moisture convergence zone; MJO, madden-Julian oscillation; MMCs, mesoscale convective complexes; MCS, mesoscale convective systems; PDO, pacific decadal oscillation; SAM, southern annular mode; SAMS, south American monsoon system; SACZ, south Atlantic convergence zone; SAH, south Atlantic high; SPH, south pacific high; SST, Sea surface temperature; ULJs, upper level jets; UTCV, upper tropospheric cyclonic vortex; VHL, virtual health library

Introduction

At the confluence of technological advancements, international agendas and agreements, and contemporary environmental challenges, understanding meteorological systems and their direct impact on communities has never been more necessary. In a world where climate change not only promises to alter global weather patterns but also to intensify the frequency and severity of extreme events, the detailed study of these systems takes on a leading role.[1] This article, situated at the intersection of meteorology and climatology with a focus on the State of Santa Catarina, Brazil, seeks to contribute to the understanding of the complex web of meteorological systems that shape the climate and extreme events in the region.

The State of Santa Catarina, located in Southern Brazil, is distinguished by its geographical and climatic diversity, often finding itself at the epicenter of extreme weather events, ranging from devastating floods to prolonged drought periods.[2] These events, often a direct result of complex meteorological systems, impact not only the local biodiversity and community life but also pose significant challenges to disaster management, urban planning, and the production of research related to meteorological and climatic phenomena.[3] In this context, the current study emerges as a response to the urgent need for a didactic understanding of these systems, aiming to improve the preparation and response to climatic adversities of both the community itself and various researches centered on local climatology and meteorology.

The prevailing trend in studies focusing on meteorological systems is the interdisciplinary exploration of this knowledge, aimed at addressing significant challenges in the realms of climate change, natural disaster risk management, and sustainable development (GOSH, 2023).[4] Given the diverse interest of various sectors in understanding local meteorology, there is a demand for multifaceted approaches to the subject, converging on the understanding that meteorological systems significantly impact various sectors, from agriculture to public health, requiring an analysis that extends beyond traditional atmospheric sciences.[5]

There's also the fact that many studies require financial and human resources, which are often scarce. Studies focused on specific locations reflect the difficulties faced by the scientific community in conducting research that requires significant investments in technology and specialized expertise.[6] Various fields need a better understanding of the meteorological variables that act in their environment but lack the necessary expertise, unlike professionals in meteorology and climatology. The tendency to prioritize issues of global or regional interest over specific local investigations may divert the necessary attention and resources from studies that could offer insights for understanding and managing risks associated with meteorological systems in particular regions.

Just as there is a need for an interdisciplinary approach that brings together knowledge from Meteorology, Climatology, Geography, and Ecology, among other disciplines, for an integrated analysis across multiple levels of knowledge, making the information accessible to beginners in the field and reinforcing the theoretical foundation of technical and robust studies is highlighted as a vital strategy to overcome these obstacles. Presenting fundamental information on Meteorology and its phenomena can offer new perspectives and methodologies for addressing challenges associated with various research obstacles, promoting a richer and more applicable understanding of meteorological phenomena and their effects.

When investigating meteorological phenomena in specific locations, researchers face a myriad of intrinsic challenges, including the complexity and variability of meteorological systems, exacerbated by unique regional characteristics, needing a meticulous approach that integrates high-resolution data and advanced models. However, data limitations, often worsened by a lack of monitoring infrastructure, represent a significant obstacle to conducting accurate and comprehensive analyses.[7] To mitigate such challenges, it is crucial to have research and a scientific basis that demonstrates phenomena and systems impacting the region of interest.

The aim of this article is to comprehensively identify and analyze the meteorological systems operating in the State of Santa Catarina, Brazil, clarifying their characteristics, scales of action, and associated impacts, particularly regarding any socioeconomic impact on society. This study seeks to fill a gap in the current scientific literature by providing a detailed framework on these meteorological systems, their characteristics, action scales, and the impact associated with potential extreme events that cause natural disasters in the state.

This article aims to provide a holistic view of the meteorological systems influencing the climate and natural disasters in Santa Catarina, serving as a reference for researchers, meteorologists, and disaster risk managers. Moreover, the findings of this study have the potential to enhance the focus on efforts directed towards the accuracy of weather forecasts and, consequently, contribute to the efficiency of studies related to monitoring and forecasting disasters in the state.

The article is structured to facilitate the reader's understanding of the complex and chaotic nature of meteorological systems, classifying them according to their scales of action - interdecadal, intraseasonal, synoptic, and mesoscale - and discussing their respective impacts on the region's climate.

Material and methods

This study employs the Bibliographic Review methodology to identify the active meteorological systems in the State of Santa Catarina, Brazil, and their impacts. This methodology was chosen due to the need to synthesize existing knowledge, filling a gap in the scientific literature with a detailed reference on these systems, their characteristics, scales of action, and impacts in a single article.

To achieve this objective, specific search criteria were established, selecting relevant keywords to the theme, such as "meteorological systems," "Santa Catarina," "extreme events," "natural disasters," and "weather forecasting." Searches were conducted in renowned scientific databases, including Web of Science, Scopus, Google Scholar, as well as national databases like the Virtual Health Library (BVS) and the CAPES Journal Portal.

The selection of materials encompassed scientific articles, technical reports from meteorological and civil defense institutions, as well as theses and dissertations, with relevance to the topic guiding the choice. The temporal scope considered included publications from the last 25 years, without prejudice to the inclusion of classic studies essential for a deep understanding of meteorological systems.

Following the analysis of the collected materials, the identified meteorological systems were classified, considering their intrinsic characteristics and associated impacts. This step allowed for a coherent organization of information, facilitating the understanding of the specific dynamics of each system and its direct relationship with events that have adverse potential in the state of Santa Catarina.

Results and discussion

Interdecadal and interannual scales systems

The Pacific Decadal Oscillation (PDO) is described by Mantua and Hare,[8] and various researchers as a long-lasting pattern phenomenon similar to the El Niño and La Niña climate variability cycles in the Pacific. Extremes in the PDO pattern are marked by irregular cyclical variations in the sea surface temperatures in the Pacific Ocean, on interannual to interdecadal time scales, classified as warm or cold.

During the alternation of warm and cold phases, significant impacts on global climate can result, affecting the formation and intensity of cyclones, changes in jet stream paths, and influencing episodes of droughts and floods around the Pacific basin, the productivity of marine ecosystems, as well as influencing global temperature patterns.[9] An analysis of some time series has identified that this phenomenon has influenced the change in precipitation trends, notably in the Western region of Santa Catarina, where a reversal trend was observed in all four seasons.[10]

Similarly, the PDO can also influence other systems like the El Niño Southern Oscillation (ENSO), potentially intensifying or mitigating the impacts of this phenomenon depending on its phase. According to Souza and Reboita[11] if ENSO and PDO occur during the same phase, the impacts of El Niño or La Niña could be amplified or attenuated. In summary, PDO events share similarities with those of ENSO, except in their temporality, where ENSO predominantly occurs with interannual variations, PDO exhibits decadal variability.

Regarding the interannual scale phenomena occurring in the Pacific Ocean, where the waters show significant temperature changes relative to the distribution of water surface temperature, leading to major alterations in the climate at a global level.[12] When this variation increases the water temperature, this phenomenon is commonly known as El Niño; conversely, when the opposite occurs, a decrease in water temperature, this phenomenon is termed La Niña.

This periodic variation in the Pacific Ocean-atmosphere system, typically occurring every 3 to 7 years with a duration of 9 to 24 months, dramatically impacts global climate and is called El Niño Southern Oscillation (ENSO). This event is associated with variations in the Sea Surface Temperature (SST) patterns and trade winds in the region between the Peruvian coast and Australia and, on a global scale, is the most significant interannual ocean/atmosphere phenomenon related to climate variability.[13]

According to studies conducted by Hermann (2001), the El Niño phenomenon has significantly influenced the incidence of natural disasters in the state of Santa Catarina. For example, the major disaster periods are associated with El Niño years, with the exception of 1984 and 2001, when such events were linked to La Niña periods.[14] During the Southern Hemisphere's spring and summer, Santa Catarina experienced more frequent extreme precipitation events during El Niño episodes caused by the development of Mesoscale Convective Complexes (MCCs) and amplified by the action of high and low-level jets associated with frontal systems and also by the advection of moisture from the subtropical Atlantic, stemming from the South Atlantic Convergence Zone (SACZ).[15]

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Similarly, El Niño has a strong influence on atmospheric circulation on a global scale, and when associated, it triggers the progression of frontal systems and consequently hydrometeorological disaster events in Santa Catarina, such as floods, hail, windstorms, and tornadoes. These tend to intensify during spring and summer periods, when there is an association with intense atmospheric instabilities, such as isolated convective systems, Mesoscale Convective Complexes, and cold fronts.[14]

According to Sampaio[12] this phenomenon operates on a global scale and can influence the climate and atmospheric conditions of various places simultaneously. In Santa Catarina, it is responsible for increasing the average temperature and for the incidence of severe storms, and its absence leads to long periods of drought, in addition to influencing the activity of the Intertropical Convergence Zone (ITCZ).

Intraseasonal scale systems

During the periods of intense rainfall in Brazil, various meteorological systems greatly influence the rain regime, such as convergence zones, cold fronts, and macroscale phenomena like ENSO. However, besides these well-known systems, another phenomenon of great importance is the Madden-Julian Oscillation (MJO).[16]

The MJO manifests as a tropical convection cell that moves from West to East along the equatorial belt over a period of 30 to 60 days. This phenomenon typically begins in the Indian Ocean as a large area of convection that produces above-normal precipitation in the region. Over time, this convection moves eastward to the Western Pacific Ocean, generating rainfall in Northern Australia and Indonesia.[17]

Once the dynamics in the Western Pacific conclude, the oscillation no longer remains coupled with the convection area, meaning it detaches from the large accumulations of convective clouds. However, this convection disturbs the atmospheric circulation at both low and high levels. In this regard, Magina[18] states that since the atmosphere behaves like a fluid, any disturbance within it propagates. Thus, the disturbance generated by the convection spreads across the globe through the Pacific, South America, the Atlantic Ocean, and the African continent, until it returns to the Indian Ocean.[18]

From this perspective, the MJO modifies areas of ascending and subsiding movements, which can either favor or hinder rain formation in Brazil, with a greater emphasis on the North and Northeast regions. However, it also affects other regions, such as the southern region and the state of Santa Catarina.[19] It is important to note that the MJO does not autonomously generate precipitation; its contribution to the rain formation process is in intensifying or inhibiting rains formed by other meteorological systems.

When the area of most intense convection is near Indonesia, anomalous subsiding movements occur over the North and Northeast of Brazil, inhibiting rainfall formation. Conversely, when subsiding movements are inhibiting rain formation over Indonesia, an area of ascending movements favors rainfall formation in Brazil.[20]

Similarly, the Antarctic Oscillation, also known as the Southern Annular Mode (SAM), represents the main pattern of climate variability in the Southern Hemisphere, notably influencing the meteorological and climatic conditions of the Antarctic region and adjacent areas.[21] This phenomenon is characterized by fluctuations in the intensity and position of the westerly circumpolar winds that surround Antarctica, impacting the distribution of atmospheric pressure between the mid and high latitudes of the Southern Hemisphere.

The SAM is determined by the atmospheric pressure difference between mid-latitudes, around 40°S to 50°S, and high latitudes, approximately 65°S to 70°S.[22] Pragmatically, it alternates between two phases, positive and negative. In positive phases, there is a greater pressure difference, resulting in stronger winds around Antarctica, effectively confining cold air masses near the pole, potentially causing higher temperatures at mid-latitudes and affecting precipitation patterns.[23] Conversely, in its negative phase, there is a smaller pressure difference, weakening circumpolar winds and allowing more movement of cold air masses towards mid-latitudes, affecting temperatures and precipitation patterns oppositely to the positive phase.[24]

The impacts of the Antarctic Oscillation are extensive and varied, affecting not just the Antarctic climate but also influencing weather conditions in distant areas such as South America, South Africa, and Australia.[25] During the positive phase of SAM, characterized by positive pressure anomalies at mid-latitudes, the South Atlantic High (SAH) tends to position further south, consequently influencing the ITCZ to move in the same direction, resulting in increased precipitation in the Northern Region of Brazil.[26]

As a result, the SAH is strengthened, inducing an increase in the activity of atmospheric blockings and/or the presence of more intense anticyclones in the Southwest Atlantic. Consequently, there is a precipitation deficit in the Central-Southern region of Brazil (except in autumn) and a strengthening of winds in specific areas of the South of the country, such as Santa Catarina.[27]

The SAM affects precipitation distribution and intensity, temperature patterns, and even the occurrence of extreme events across various parts of the Southern Hemisphere, influencing fresh water availability, aquifer recharge, and surface runoff patterns in specific regions. According to Pizzochero et al.,[28] during the negative phase of SAM, there is a predominance of negative temperature anomalies across much of Brazil, indicating lower than normal temperatures, except from the coast of Bahia to Santa Catarina, where there is a regional variation in the influence of this phenomenon.

Synoptic systems

Cyclones

Among the phenomena with the greatest potential for severity at the synoptic scale, playing a key role in atmospheric conditions and dynamics, are cyclones. These events can be characterized as winds moving in an internal spiral rotating around a zone of low atmospheric pressure, meaning a large mass of air rotating around a low-pressure center counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere, opposite to an anticyclone.[29]

Cyclones can also be considered as regulators of temperature contrasts between the poles and the Equator region and maintain westerly winds at mid-latitudes against frictional dissipation. Thus, they are responsible for the balance of energy and water vapor in the atmosphere.[30] Cyclones exhibit variations in their formation; however, regardless of the type of cyclone, whether extratropical, subtropical, or tropical, they are characterized by having lower atmospheric pressure than their surroundings.[31]

Regarding the formation or intensification of this phenomenon, it occurs when there is a decrease in atmospheric pressure at the surface in the lower and middle levels of the troposphere, consequently leading to the formation of a cyclonic circulation called cyclogenesis.[32] This process can occur on both a microscale and a synoptic scale, and the classification of such phenomena is based on the variables that lead to their formation, such as the association of cold fronts, sea surface temperature, and the location of their formation. When this cyclonic formation weakens or dissipates due to an increase in atmospheric pressure and the horizontal temperature gradients weaken, and the system loses intensity, i.e., when the opposite process of cyclogenesis occurs, this process is called cyclolysis.[29]

According to Marrafon et al.,[31] certain cyclone events exhibit a pattern in relation to the region of the globe where they emerge, which is reflected in their classification. For example, cyclones known as tropical generally tend to form between the Tropic of Cancer and the Tropic of Capricorn, in the latitude band between 20°S and 20°N. Between latitudes of 20° and 30° in both hemispheres, the formation of both tropical and extratropical cyclones can be identified, but in this band, subtropical cyclones are more common.[33] However, at latitudes beyond 30°S and 30°N, only the cyclogenesis of extratropical cyclones is recorded.

One distinguishing feature of extratropical cyclones, suggesting their occurrence in certain regions, is that their cyclogenesis is associated with cold fronts, unlike subtropical and tropical cyclones, which do not have cold fronts associated with their formation.[31] In the Southern Hemisphere, Antarctica is the region where almost all cold fronts and associated extratropical cyclones form, making it essential for the emergence of such types of events.[34]

Furthermore, another factor differentiating cyclone classifications is related to the temperature found at the center of such events. According to Marrafon et al.,[31] near the surface, the center of extratropical cyclones exhibits a lower temperature, that is, colder than the surrounding atmosphere, while the center of subtropical cyclones tends to be warmer than the surrounding atmosphere. This difference, exhibited by subtropical cyclones, influences the atmosphere by making it more unstable and increases the conditions for the emergence of severe storms.

According to De Jesus et al.,[34] subtropical cyclones have a smaller horizontal structure than extratropical cyclones and, due to this characteristic, can cause more severe weather conditions in localized regions, consequently leading to higher volumes of rain and stronger winds than extratropical cyclones. It's also worth noting, as a characteristic of subtropical and tropical cyclones, that the low-pressure cores at different atmospheric levels are overlaid, as if "stacked" on top of each other, from the surface to higher levels of the atmosphere, causing such events to vary greatly in size.[35]

Regarding extratropical cyclones, their low-pressure centers do not exhibit vertical alignment similar to that seen in tropical and subtropical phenomena. Their formation is associated with the presence of horizontal air temperature gradients at the surface and waves traveling from west to east in the mid and high troposphere, approximately 5,500 to 10,000 meters in height,[31] meaning the low-pressure areas at altitude are displaced eastward relative to the surface low center.

Based on the research by Reboita and Marrafon (2021), cyclones classified as extratropical are systems that occur more frequently along the Brazilian coast, particularly affecting the southeast coast and the southern region of the country. This study identified Santa Catarina as a region of concern due to the proximity of cyclone formation to the state's coast. These phenomena are more common in these areas due to ideal conditions for their formation, such as horizontal temperature variations near the surface and the constant presence of cold fronts in the atmosphere.[36]

On the other hand, subtropical and tropical cyclones develop from distinct elements, such as high sea surface temperatures, accumulation of significant moisture near the surface, and the presence of a developing cold cyclone at mid-levels of the atmosphere, around 5 kilometers in height. This condition is not common in the region near Brazil and is necessary for the formation of this type of cyclone.[31]

Furthermore, regarding the monitoring and forecasting of cyclone events through satellite images, subtropical and tropical cyclones are recognized as a mass of clouds with more rounded characteristics, unlike extratropical cyclones, which are identified by their spiral shape.[37]

South Atlantic convergence zone (SACZ)

The South Atlantic Convergence Zone (SACZ) can be defined as a persistent band of cloudiness and precipitation, oriented Northwest-Southeast, semi-stationary, typically occurring between October and March (spring and summer). It extends from the Southern Amazon through the Central-West Region and into the Atlantic Ocean, bringing potentially intense rainfall.[38]

According to the studies by Quadro[39] this phenomenon is mainly observed in the summer, when this cloudiness line crosses Brazil from Northwest to Southeast. Along its entire length, strong storms can be observed, making it one of the main contributors to the rainfall regime in South America and the regions where it operates. It is formed by the interaction of various other meteorological phenomena typical of this season and is the primary source of precipitation in the Midwest, Southeast, and South of Brazil.

Resulting from the action of wind circulation from various meteorological systems operating simultaneously, known as the South American Monsoon System - SAMS, which produces a high concentration of moisture in mid-spring over Equatorial Amazonia, the formation of the SACZ occurs.[40] Regarding the local factors that favor the occurrence of such a phenomenon, the action of the trade winds stands out, which, when intensified, transport more moisture to the Northern region of Brazil in the spring than at other times of the year,[41] as well as the confluence between the South Atlantic Anticyclone - SAH with air from higher latitudes near the equator.[30]

Moreover, the moisture transported from the Tropical Atlantic Ocean to the Northern region of Brazil, combined with the evapotranspiration from the Amazon forest, not only contributes to precipitation in that region but is also partly transported to the South and Southeast of Brazil. This is due to the presence of a trough east of the Andes Mountains, which facilitates the flow of moisture from the Amazon region through winds at the East of the Andes known as Low-Level Jets (LLJs) (SANTOS and REBOITA, 2019).

According to Reboita et al.,[42] when this moisture forms in the summer, resulting from the interaction of LLJ systems, fronts, and winds from the South Atlantic High, it becomes a Moisture Convergence Zone (MCZ) over the continent. As understood by the Weather Forecasting Group of the National Institute for Space Research (GPT/INPE), the MCZ extends Northwest-Southeast from the Amazon to Southeastern Brazil and the South Atlantic Ocean. If it acts for three days or more, it is termed the South Atlantic Convergence Zone.[40,43]

As a result, a predominant characteristic of this phenomenon is the persistence and intensity of rainfall, due to this system being a connection between cold fronts in the ocean and extensive areas of instability over the interior of Brazil. This connection leads to climate disruptions resulting from intense heat during the day followed by intense storms. According to the ideas of Seluchi and Chou (2009), Reboita et al.,[36] and Alves et al.,[38] such characteristics of this system can cause floods, flash floods, landslides, and hillside slips in certain susceptible and vulnerable regions, or even weaken and inhibit convection for several days, being responsible for sequences of rainy days, which often end up causing extreme precipitation events.

In Santa Catarina and other regions of Southern Brazil, the South Atlantic Convergence Zone indirectly influences, like the other systems that form it or direct its path further south. This system acts climatologically over Southeastern Brazil but can induce intense descending movements in Southern Brazil, inhibiting cloud formation and precipitation.[40,42,44]

South Atlantic subtropical high (SAH) and south pacific subtropical high (SPH)

Phenomena known as anticyclones are defined as areas of high pressure, typically above 1013 Pa, with a diameter of about 1000 to 3000 kilometers, where the atmospheric pressure is higher than the surrounding air pressure and increases from the periphery towards the center, rotating clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. According to Oliveira,[30] their formation is associated with the general circulation of the atmosphere, involving the Coriolis force, the convergence of jet streams, and subsidence winds developed at the meeting of the Hadley and Ferrel cells at 30° North or South.[45]

According to Reboita et al.,[46] anticyclones can be classified into two main groups: migratory or transient types, which occur occasionally with a duration of 2 to 6 days associated with baroclinic conditions (where isobars and isotherms do not coincide), and semi-permanent types, which persist for most of the year in subtropical latitude regions known as Subtropical Anticyclones or Subtropical Highs. In the Southern Hemisphere, over the oceans, there are three subtropical anticyclones that influence the weather and climate in the region: the Mascarene High in the Indian Ocean, the South Atlantic Subtropical High (SAH), and the South Pacific Subtropical High (SPH), with the latter two having the most significant influence on the climate in South America.[38,30]

The SAH, also known as the Saint Helena Anticyclone due to its proximity to the Saint Helena Island, the nearest landmass at this latitude, is a semi-permanent high-pressure system that regulates the dry and rainy seasons across much of South America, particularly in the Brazilian region. Depending on the position of this system and its seasonal movement, the SAH can significantly influence the precipitation regime and meteorological events in certain regions of Brazil or prevent the formation of precipitation.[30]

During the winter periods, this system acts closer to the continent and can inhibit the entry of cold fronts, cause thermal inversion, and concentrate pollutant constituents in the main urban centers of the Southeast and South regions due to the formation of an atmospheric blockage caused by atmospheric subsidence, which reduces the region’s moisture.[47] Thus, the SAH contributes to lower rainfall regimes, temperature drops, and also favors the formation of fog and frost in the South and Southeast of Brazil.[42]

Vieira and Cupolillo[48] note that from June to September, the incidence of the SAH results in the establishment of a hot, dry, stable atmosphere with a lack of cloudiness and precipitation. During this period, extreme episodes of low relative humidity occur when the process of continentalization of this phenomenon takes place. At the beginning of the rainy season, the weakening of East/Northeast winds and the intensification of Northwest flow can occur, responsible for transporting moisture from the Amazon to the Southeast and South of Brazil.[39] Reboita et al.[49] also support this statement by suggesting in their studies that in the Southeast region, in addition to the moisture from the Amazon, another important source of moisture is the South Atlantic Ocean, which comes from the SAH when it is further East during the rainy season.

As a result of the intensification of the Northeast trade winds, moisture transport to the Amazon increases considerably when the Low-Level Jets return part of this moisture, as well as receive moisture from the influence of the SAH. This favors moisture transport to the continent when the High is displaced over the Atlantic Ocean.[42]

Vieira and Cupolillo[48] also highlight that even when the SAH phenomenon is further away from the continent during the rainy season, there is still a possibility of its advance over Brazil. This can result in reduced precipitation and increased temperatures, known as a climatic “veranico,” or dry spell, which are short periods of drought during the rainy season, typically lasting between ten to twenty days.

Similarly, the South Pacific Subtropical High (SPH), as the name suggests, is a semi-permanent system that operates over the Pacific Ocean near the coast of Chile and directly influences the climate of Chile, Peru, Ecuador, Bolivia, and Argentina. According to Reboita et al.,[42] the SPH is the atmospheric system that influences the precipitation regime over the Southern and Southwestern regions of South American countries, where the Southernmost region exhibits uniform precipitation throughout the year, unlike the Southeastern region, which experiences its annual maximum during winter and its minimum during summer.

The South Pacific Subtropical High reaches its Northernmost position during the winter months, resulting in westward winds encountering the Andes and, upon crossing, favoring windward rain in the mountainous regions. However, during the summer, the phenomenon moves southward, where a predominance of descending movement due to high pressure inhibits cloud formation and precipitation.[30]

Aguirre[50] remarks that the SPH significantly contributes to the extreme arid climate extending from the Pacific Desert, located in Northern Chile (Atacama Desert), to the coast of Peru (coastal desert). This high-pressure system plays a crucial role as a driver of the Southeast Pacific trade winds, as well as a driver of the Humboldt Current and as one of the elements of the ENSO climate pattern.

Regarding the impact of the SPH on Brazil, studies by Lucyrio et al.[46] observed at the surface that there was an incursion of polar air to lower latitudes due to the circulation characteristics of the SPH associated with low pressure in the Atlantic Ocean, favoring the advection of cold air, i.e., the occurrence of intense cold waves in the Southeast and South regions of Brazil. Ribeiro and Nunes[51] identified in their studies that the SPH can also influence Southern Brazil when it acts as an atmospheric block, preventing the passage of frontal systems, which can lead to heatwaves in the region over short periods.

Upper-tropospheric cyclonic vortices (UTCV)

The Upper-Tropospheric Cyclonic Vortex (UTCV) is classified as a closed wind circulation system with low pressure that rotates clockwise, originating at high atmospheric levels and potentially extending to lower levels depending on cloudiness and atmospheric conditions, featuring a cold core.[52] The formation area of the UTCV varies with the season; for instance, in Brazil, it typically occurs during the summer months in the Northeast and throughout the winter and spring near the South region.

Gan et al.[52] highlight that UTCVs can be distinguished into two types of phenomena: those that are formed in subtropical latitudes, known as Palmén, such as those affecting the Southeast and South regions of Brazil, and those forming in tropical regions, like those acting in the Northeast of Brazil, also referred to as Palmén type. In the case of Northeastern Brazil, such a system has the potential to induce precipitation over certain areas, while in other locations, it acts as an atmospheric block inhibiting precipitation.[53]

Several factors and variables, when combined, can influence the formation of UTCVs, but some variables have a greater influence on their formation and appear more frequently when such vortices are identified. The classic formation of the UTCV in the Northeast is associated with cold fronts advancing towards the Northern coast of the Southeast and the Southern coast of Bahia. It is also intensified when the Bolivian High System - BHS acts at high atmospheric levels near the Central-West of Brazil, significantly contributing to the vortex formation.[54]

In South America, the summer atmospheric circulation shows that the Bolivian High's formation is associated with the release of latent heat in the Amazon region. When this occurs, the air currents below the BHS form a trough between the Northeast of Brazil and the Atlantic Ocean, which can eventually result in the appearance of UTCVs within the trough.[36] The formation of the UTCV in the Northeast region is also associated with the intensification of the SACZ, which is one of the main systems responsible for heavy rains during the months of December, January, and February between the North and Southeast of the country.[38]

Similarly, the subtropical UTCVs that influence the meteorology of Brazil is formed with certain frequency at the extreme Eastern edge of the South Pacific Ocean, and when they manage to cross the Andes Mountains, they cause meteorological changes in the Central South of Brazil and in some South American countries such as Uruguay and Argentina. According to Gan et al.,[52] when UTCVs advance towards the continent, they can cause instability in the region's atmosphere, for example, when the cold and dry air inside the vortex influences the formation of cold waves through radiative loss at mid-levels, which favors the occurrence of frosts in the South of Brazil, causes strong winds and even snow in regions with altitudes above 1000 meters, in addition to causing cyclogenesis at the surface.

Weather fronts systems

Among the phenomena and systems that span hundreds to thousands of kilometers, which can last for several days or weeks and are frequent in Brazil, such as the SACZ, are the Weather Front Systems or Frontal Systems. These cause variations in precipitation and temperature distribution across nearly all of Brazil and South America.[44] To address frontal systems in an educational manner, it is necessary to delve deeper into the phenomena known as fronts, which are related to the formations of frontal systems.

Fronts form when air masses with distinct characteristics in terms of their thermal gradients meet, and in this case, the South and Southeast regions are considered conducive to frontogenesis.[52] The cold air from the poles and the warm air from the tropics and subtropics are separated by fronts or frontal systems. According to Vecchia et al. (2020), through the dynamics of atmospheric waves and fronts, heat is distributed, reducing the excess in the tropics and the deficit at the poles. When cold air advances over a certain terrestrial sector, the front is called a cold front, as opposed to when warm air overlaps another terrestrial sector, it is called a warm front.

Thus, when two fronts with different thermal characteristics meet, they are referred to as frontal systems. For example, when the cold air from one air mass advances and replaces the warm air from another mass, a leading edge of the frontal zone is outlined, which is marked by a cold front.[52] In this sense, Alves et al.[38] also consider as a classic frontal system one that has in its composition a cold front, a warm front, and a low-pressure center (cyclone) at the surface.

Similarly, frontal systems occur throughout the year, with the second half being more prominent since the highest number of occurrences at higher latitudes are identified between April and November.[38] Escobar et al.[44] consider the period between May and September to be when cold fronts most frequently affect Santa Catarina, unlike the period between October and April, when this frequency is lower.

Cold fronts move from South to North (in relation to the Southern hemisphere) and can reach as far as the South of Pará, where they cause the "friagens" (cold fronts). It is responsible for large amounts of precipitation, followed by good and cold weather. However, the warm front moves from North to South, in the Southern hemisphere, does not cause much rain, and leaves the weather warmer after its passage.

During winter, these systems are accompanied by air masses from high latitudes that sometimes cause frost and cold snaps in agricultural areas in the Southeast and South of Brazil. Occasionally, cold fronts reach very low latitudes over the Western Amazon and also along the Northeast coast of Brazil.42 When the cold fronts move northward (towards the equator) during the summer season, they sometimes interact.[52]

Cold fronts are the most common weather systems that alter weather conditions over the central-southern part of the South American continent. Studies by Kousky and Andrade (2022) show that the spatial distribution of frontal activity over South America has two preferred regions with a higher frequency of frontal passages, the first being east of the Andes Mountain Range and the second over the coastal regions of the South and Southeast, influenced by the presence of the Serra do Mar. Reboita et al.[42] and Escobar et al.[44] discuss that, given this result, the eastern region of Santa Catarina can be considered one of the areas with the highest frequency of frontal system passages in Brazil.

Jet streams (upper-level jets and low-level jets)

Jet streams can be considered as the intense flow of air that occurs in the atmosphere, which act as a regulatory element of the atmosphere and are responsible for changes in weather conditions around the world. When these currents are found in the tropopause, in the transition range between the tropopause and stratosphere, these currents are called Upper-Level Jets (ULJs). However, when this intense air flow occurs in the lower troposphere, these currents are called Low-Level Jets (LLJs). These strong winds are present in both hemispheres and are extremely important for the development of meteorological systems.

At Upper levels, jet streams occur due to the rotation of the planet and the temperature variation between the tropics and the poles, guided from West to East in an indirect manner, transitioning from North to South in a wave-like pattern, alternating from regions of high pressure to low pressure.[55] In the tropics, the troposphere is deeper (16 km) compared to the poles (11 km), due to the heat causing the air column to expand. However, despite the air columns in the tropics and at the poles having on average the same mass, the atmospheric pressure is different at equal altitudes, due to the air density vertically decreasing more rapidly at the poles.[56]

According to Oliveira,[30] the ULJs can be classified into the Subtropical Jet, which appears as a narrow band of intense wind on both sides of the equator at approximately 200 hPa, whose formation is associated with the Hadley Cells, located at latitudes between 20º and 35º South and are more intense and closer to the equator in winter, as well as the Polar Jet, located between the latitudes of 35º and 70º South, its formation linked to the horizontal temperature gradient presented in narrow frontal zones and acts more frequently in winter, especially at lower latitudes, where its position is closer to the equator.

In general, the Upper-Level Jet Streams can increase the vorticity gradient in certain regions to such an extent that the atmospheric waves of these currents can affect atmospheric vortices, such as anticyclonic blocks, and can create prolonged weather conditions that may lead to extreme climatic impacts.[55] In Brazil, during the winter, cold fronts reach lower latitudes and are usually accompanied by the Polar Jet in their movements. Unlike in summer, when the Polar Jet is restricted to higher latitudes, having its position further north near 35º South. Also, when the Subtropical Jets impact at low latitudes, the Polar Jet always appears coupled to this system, since it is associated with transient systems.[52]

On the other hand, Low-Level Jets are high-speed air currents that occur close to the Earth's surface, usually at an altitude of 1 to 2 kilometers. These jets can occur on different scales, from small local areas to large continental regions. LLJs play a very important role in global atmospheric circulation due to their responsibility for the advection of heat and moisture from the tropics to mid-latitude regions. Brizola et al. (2018) define LLJs as meridional flows that can be found in the first few kilometers of the atmosphere, with their maximum speed around 2,000 meters above the Earth's surface.

LLJs can be considered an important mechanism for atmospheric moisture transport, similar to Atmospheric Rivers, and are responsible for precipitation events, as they intensify or reduce moisture transport, resulting in rainfall anomalies mainly east of the Andes.[57] These meteorological phenomena can affect the climate and weather in various regions of the world, especially when they are intense, as they can influence the formation and intensity of other systems like cyclones and cold fronts, in addition to affecting the transport of moisture and pollutants in the atmosphere, impacting air quality and human health.

Regarding the formation of LLJs, they can be associated with two types of processes, those associated with atmospheric boundary layer (ABL) processes or those associated with synoptic-scale phenomena. The ABL LLJ typically shows a strong oscillation during the daytime and is intrinsically linked to the horizontal temperature gradient produced by sloping terrains during this period. However, synoptic LLJs are associated with the intensification of horizontal pressure gradients induced by migratory baroclinic systems, which can also be linked to upper-level jet streams resulting from transverse ageostrophic circulation.[58]

The Andes Mountains act as a topographical barrier and channel the trade winds coming from the Tropical North Atlantic, which pass through the Amazon basin towards the subtropics. This modifies the dry dynamics with moist convection on the slopes of the Andes and causes cyclonic disturbances in the Westerly flow in Northern Argentina, leading to variations in the pressure field. This contributes to the flow being directed from the North Atlantic towards the La Plata basin through the Amazon basin.[59]

In Brazil, LLJs are common during the summer period, especially in the Central-South region, where these jets are generated by the contrast between the warm and humid areas of the Amazon and the drier and colder areas of Southern Brazil. As a consequence of this moisture transport, Santa Catarina, situated in the Southern region, and adjacent countries such as Uruguay, Paraguay, and part of Argentina have their weather and climate conditions affected by the low-level jet coming from the East of the Andes. This phenomenon also regulates the rainfall regime in the region, as it influences both the destabilization of the atmosphere and the triggering of deep convection when interacting with transient systems and with the local topography, which consequently plays a crucial role in the formation and development of severe storms that develop in the jet's exit region.[30]

When low-level jets occur, they can bring moisture from the Amazon to the Central-South region of the country, which can result in intense and prolonged rainfall. However, LLJs can also cause droughts in some regions, especially when they occur persistently. Low-level jets pose a significant challenge for weather and climate forecasting, as they are small-scale phenomena that can be difficult to detect and accurately simulate in numerical models. Therefore, careful studies and observations are necessary to better understand these phenomena and improve weather and climate forecasting.

Meso-scale systems

Mesoscale convective complexes

In terms of mesoscale events, the phenomena are somewhat larger, with an extent of several tens of kilometers and a duration of several hours. They are influenced by surface characteristics and, primarily, by the process of convection. Mesoscale Convective Systems (MCSs) are the main phenomena of this scale and can occur in isolation or in groups. These systems are typically formed in tropical and subtropical regions, where there is a strong gradient of temperature and humidity, and are also responsible for a large part of the precipitation in many regions of the world and can be accompanied by strong winds, lightning, and hail.

In this context, among the mesoscale convective systems, the Mesoscale Convective Complexes (MCCs) are a specific type with particular spatial and temporal organization. MCCs are composed of an area of organized convective clouds in a circular or oval pattern, with a typical diameter ranging from 100 to 500 km, which consist of a set of convective Cumulonimbus (Cb) clouds, thick and cold, with vertical growth over a period of 6 to 12 hours. MCCs are often associated with events of intense precipitation.[60]

Additionally, the most distinctive characteristics of MCCs are observed during the nighttime, both in subtropical and tropical regions. These systems typically initiate their life cycle a few hours after the formation of convective cells, which occur in the late afternoon or early evening. However, their maximum extent occurs during the early morning hours, persisting until the following morning.[61] These systems are of great interest due to the consequences of the various adverse phenomena associated with MCCs, such as intense precipitation and thunderstorms.

Mesoscale Convective Complexes (MCCs) exhibit intense convective activity, with clouds extending vertically to great altitudes, resulting in a large volume of precipitation over a short period. This phenomenon can cause significant damage to society, including flooding, floods, and landslides, leading to substantial economic and social losses (LIMA et al., 2018). On the other hand, the convection caused by MCCs can provide a significant amount of rain during periods of severe drought, being critically important for populations in areas like the Northeastern hinterlands.[61]

According to Ferreira,[62] most MCCs are of continental origin and occur during the night. In this regard, although there is a higher frequency of smaller MCCs in the United States compared to South America, the characteristics of these systems in both continents are quite similar. However, a significant difference is that South American MCCs can be up to 60% larger than those formed in the United States.

In relation to South America, these phenomena are related to synoptic scale and mesoscale processes that favor their development, particularly during the summer periods, when MCCs have their maximum activity in Paraguay, Northern Argentina, and Southern Brazil, indicating a common static stability in this season.[63] Such phenomena are responsible for intense storms in the Southern region of Brazil and can cause significant damage related to strong winds, atmospheric electrical discharges, intense rainfall, and, in more extreme cases, even hail.[62]

Squall lines

Instability lines also known as Squall Lines are likely the most common form of mesoscale convective organization in which several storm cells cluster into a line, which may not necessarily be continuous, and can move across kilometers and last for several hours. On special occasions, a line can last more than a day and are likely the most common form of mesoscale convective organization.[64]

They are areas or zones where there is a large amount of energy accumulated in the atmosphere, usually associated with abrupt changes in temperature, atmospheric pressure, and humidity, which can dissipate this energy in the form of storms and intense weather systems, such as torrential rains, hail, strong winds, and tornadoes.[65]

These squall lines typically occur in regions where there is a sharp gradient of temperature and humidity, such as at cold fronts, low-pressure areas, and air mass convergence zones. Additionally, factors like topography, the presence of water bodies, and the influence of larger meteorological systems, such as hurricanes and cyclones, can enhance atmospheric instability in a specific region.[66]

Squall lines can manifest in different ways, depending on local meteorological conditions. In some cases, they appear as a distinct line of charged clouds, while in other instances, they may present as a broad area of atmospheric instability, with charged clouds spread out in various directions. Ferreira and Cavalcanti (2022) argue that in Brazil, it is common for Squall Lines to form along the North-Northeastern coast of South America, which have the potential to move inland and cause significant rainfall amounts.

These phenomena can have a significant impact on local weather and climate. Squall lines can cause intense storms, flooding, and landslides, damaging agriculture and urban infrastructure.[67] Strong winds and hailstorms can also cause damage to buildings and equipment, in addition to disrupting electricity supply and transportation services.

In Southern Brazil, during spring, the occurrence of Squall Lines is more common, and this period also sees the highest percentages of severe events, although most occur during the early morning and morning hours. The highest percentage of severe Squall Lines is recorded in the afternoon (RIBEIRO, 2018). It is important to note that such events with faster displacement are more likely to be severe, especially if the movement is faster than 50 km/h.[52]

According to Ribeiro,[68] the Squall Lines in Southern Brazil have different characteristics from tropical ones and receive little attention from the meteorological community. This results in limited scientific knowledge and low predictability of these systems. Furthermore, a study conducted by UFSC/CEPED (2013) found that windstorms are responsible for 5% to 15% of natural disasters in Southern Brazil, causing annual losses of hundreds of millions of *reais* (Brazilian currency). It is important to highlight that such figures are significant in relation to the annual damages caused by meteorological phenomena in the region.

Since these systems have a temporal scale associated with diurnal variability (sea breeze and land heating), their maximum convective activity can often be observed in satellite images in the late afternoon or on the day following their formation.66 This information is crucial for predicting the occurrence of extreme meteorological phenomena, as these phenomena are monitored by meteorological services that use advanced computational models and satellite data to forecast their occurrence and intensity. This allows authorities to issue alerts and take precautionary measures to minimize the damage caused by these events.[69–79]

Conclusion

According to the results obtained, 62 manuscripts were analyzed, where it was possible to identify the complexity and diversity of the meteorological systems influencing the climate of the State of Santa Catarina, ranging from long-term influences to short-duration local phenomena. The research identified the significant role of interdecadal phenomena, such as the Pacific Decadal Oscillation and El Niño, which determines climate patterns that extend for decades, influencing temperature and precipitation. Similarly, intraseasonal systems, particularly the Madden-Julian Oscillation and the Antarctic Oscillation, are fundamental for understanding climatic variations within the same season, directly impacting the occurrence of extreme weather events in the state.

In the meantime, the analysis of synoptic systems revealed the significant activity of cyclones, the South Atlantic Convergence Zone (SACZ), the South Atlantic Subtropical Anticyclone (SAH), and the South Pacific Subtropical Anticyclone (SPH), Upper-Tropospheric Cyclonic Vortices (UTCV), Weather Front Systems, and Jet Streams (Upper-Level Jets and Low-Level Jets) in shaping the short-term weather in Santa Catarina. These systems are the main drivers of significant events, affecting safety, the economy, and the environment. On the mesoscale, Mesoscale Convective Complexes and Squall Lines were identified as crucial in generating intense precipitation and storms, highlighting the importance of their forecasting and associated risk management.

At the microscale, although not identified in the research, represents a scale of highly active meteorological phenomena that is necessary for understanding the fine interactions that affect local climate, highlighting the impact of geographic characteristics and specific microclimatic variations in Santa Catarina.

It is worth noting that these identified systems do not represent an exhaustive list, considering that the results were obtained through a thorough analysis of the available academic content accessible in the databases highlighted by the methodology, presenting a possible limitation of this study, which does not result in a detriment to the content and scientific relevance.

The integration of these analysis scales and the identification of active systems in the state can contribute to the needs of various sectors, especially those that use a holistic approach in meteorology, aiming for a better understanding and forecasting of meteorological systems.

As a suggestion, it is necessary for future research to continue exploring these complex interactions, to advance in scientific knowledge and practical application in areas such as disaster prevention, strategic planning, and adaptation to climate changes. Thus, this study not only contributes to the academic field of Meteorology and Climatology but also offers substantial aspects for various segments in the academic, scientific, public policy, and risk mitigation strategies in Santa Catarina.

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Conflicts of interest

The author declares there is no conflict of interest.

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