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Impacts of Climate Change on the South American Monsoon System



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Summary

Monsoon systems control rainfall patterns over land in the tropical belt, where billions of people rely on a source of fresh water to sustain food and energy production. In tropical South America, millions depend on monsoonal precipitation for farming, hydropower, and freshwater supply. Unique ecosystems, such as the Brazilian savanna (Cerrado), the Amazon and Atlantic rainforests, and the Pantanal and Caatinga biomes, have adapted to the alternation between dry and wet seasons, with their survival hinging on the regularity of the rainfall regime. Anthropogenic drivers may disrupt the monsoon water cycle, reinforcing or offsetting climatic oscillations that are part of its natural variability. These drivers may impact the monsoonal onset, demise, and the frequency and intensity of extreme rainfall, exacerbating droughts and wet periods. The South American Monsoon System (SAMS) is unique. The vast tropical area of South America within the Southern Hemisphere, the Amazon rainforest, and the elevated cross-continental Andes Mountains are special features that contribute to the intricate “machinery” responsible for the maintenance and regularity of the monsoonal cycle, despite the lack of circulation reversal observed in other monsoon systems. Another feature that characterizes the SAMS is the presence of a persistent diagonal convergence zone, known as the South Atlantic Convergence Zone (SACZ). The SACZ regulates hydrological cycle in densely populated areas of South America. Furthermore, the geographic position of South America between two ocean basins and the narrowing of the continent toward midlatitudes are important factors that significantly influence midlatitude Rossby wave trains, which in turn modulate circulation and convection in the SAMS and the SACZ. Despite the sparse and intermittent records across critical geographic areas within the SAMS influence, historical data indicate that the SAMS cycle, precipitation distribution, and intensity have changed from the last 2 decades of the 20th century to the first 2 decades of the 21st century, possibly in response to the anthropogenic climate change. Global Climate Models indicate that these changes may continue and even exacerbate by the middle and end of the 21st century. The increase in extreme precipitation events and a shorter wet season appear as prevailing trends of the SAMS in models, largely corroborating observations from the first decades of the 21st century.

Keywords: SAMS, climate change, South Atlantic Convergence Zone, climate variability, South America, CMIP6 models, precipitation, monsoon cycle

Subjects: Climate Systems and Climate Dynamics, Future Climate Change Scenarios, Climate Impact: Extreme Events

The SAMS Climatic Features

The SAMS stands as the dominant circulation and precipitation pattern across tropical South America (Carvalho & Cavalcanti, 2016; Liebmann & Mechoso, 2011; Marengo et al., 2010; Silva & Carvalho, 2007; Silva Dias & Carvalho, 2017; Vera, Higgins, et al., 2006). Climate forcings exert their influence on the SAMS across a spectrum of timescales—from synoptic (short-term) to millennial (long-term). Studies such as Cruz et al. (2009), Vuille et al. (2012), Novello et al. (2017), and Bahr et al. (2021) exemplify this fascinating problem.

Like any other monsoon system, the SAMS is driven by ocean–atmosphere seasonal contrasts in heating (Fu et al., 1999, 2001). South America’s extension into the tropics enhances these contrasts. The high elevations of the Andes and the relatively large extent of the Bolivian plateau play a similar, though less pronounced, role in the SAMS as the Tibetan Plateau does in the Asian monsoon (Wu et al., 2019). The onset of the wet season over the Brazilian High Plain (considered the core of the SAMS) is typically observed between October and November (Raia & Cavalcanti, 2008; Silva & Carvalho, 2007). However, regional variations exist, as observed by Nieto-Ferreira and Rickenbach (2011). Conversely, the withdrawal of the SAMS precipitation typically occurs between March and April. Both transitions unfold gradually, setting the SAMS apart from some other monsoon systems (Rao et al., 2024). Daily precipitation over the SAMS domain progressively increases after the onset, reaching its maximum between December and February (Liebmann & Marengo, 2001; Silva & Carvalho, 2007).

A unique feature of the SAMS is the presence of a persistent diagonal convergence zone known as the South Atlantic Convergence Zone (SACZ; Carvalho et al., 2004; Kodama, 1992). The SACZ is the main contributor to the water resources in densely populated areas of eastern Brazil and in La Plata Basin (Figure 1), a region commonly referred to as Southeastern South America (SESA). However, the SACZ exhibits a complex behavior. It has been shown that the SACZ has a continental (continental–SACZ) and an oceanic (oceanic–SACZ) component, which are driven by distinct mechanisms (Carvalho et al., 2004, 2011; Carvalho, Jones, & Liebmann, 2002; Pezzi et al., 2023; Rosa et al., 2020).

Figure 1 highlights the differences between the SAMS and the SACZ by showing results from Combined Empirical Orthogonal Function (CEOF) analyses performed with 30 years of daily 850 hPa meridional and zonal winds, temperature and specific humidity, and precipitation (annual mean removed) from the Climate Forecast System Reanalysis (Saha et al., 2010). Relationships between the SAMS and seasonal anomalies of circulation at 850 hPa have been demonstrated in Zhou and Lau (1998). The first CEOF (black), with a pronounced seasonal cycle, is referred to as the Large-scale Index for the South American Monsoon (LISAM) in Silva and Carvalho (2007). The second CEOF (red), with a more transient behavior, is attributed to the oceanic–SACZ. Correlations between LISAM (first CEOF) and daily precipitation from the Tropical Rainfall Measuring Mission (TRMM; Huffman et al., 2007) are shown in Figure 1b. Positive correlations (solid lines) enclose the SAMS precipitation domain, whereas negative correlations (dashed lines) indicate seasonably dry

conditions during the SAMS. Conversely, correlations between TRMM and the second CEOF (Figure 1c) indicate the seesaw pattern in precipitation that is typically associated with the oceanic-SACZ, highlighting its influence in populated areas of La Plata Basin and eastern Brazil.

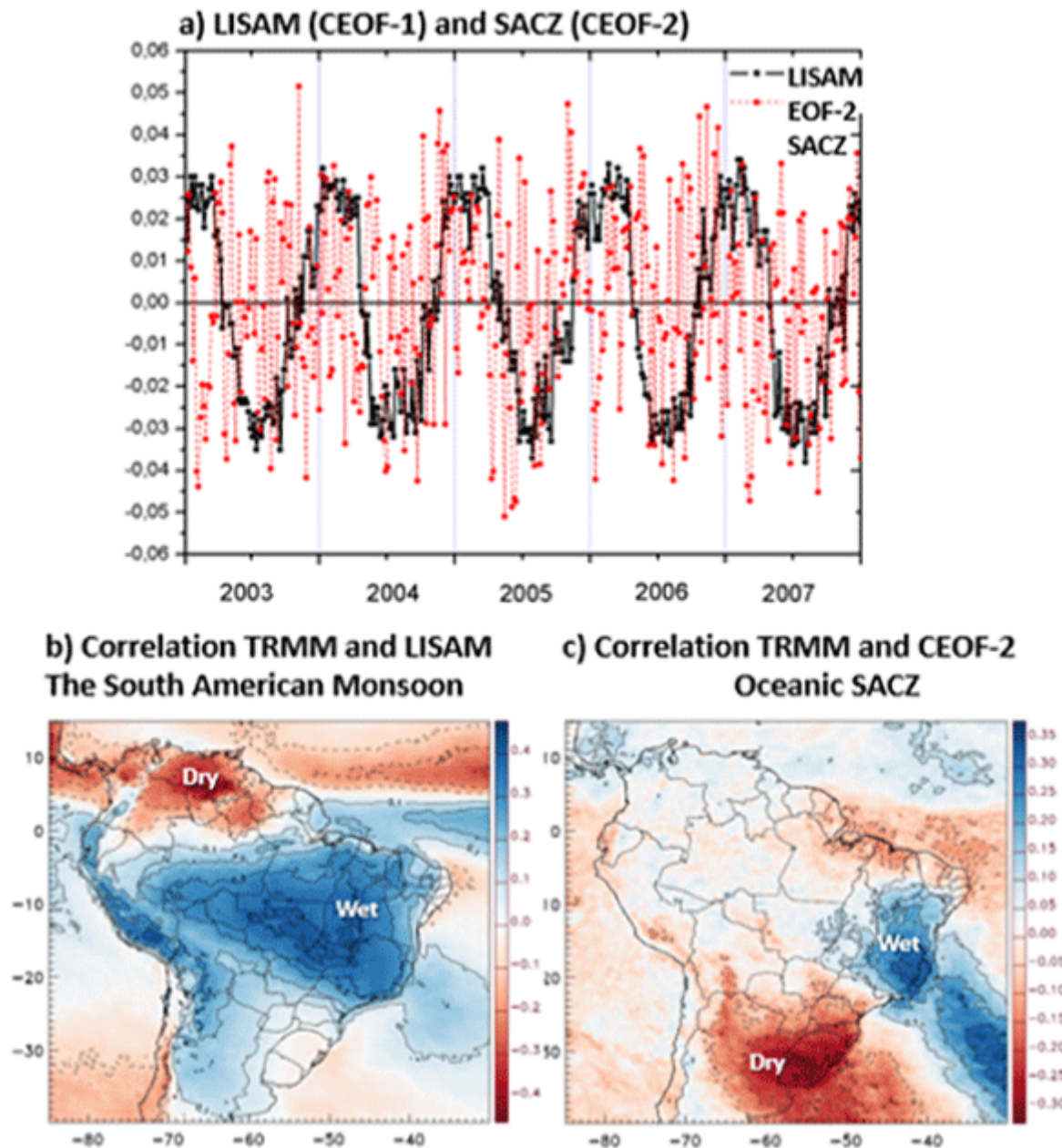


Figure 1. The SAMS and the oceanic-SACZ precipitation patterns: (a) Example of the time series of the first (black) and second (red) Combined Empirical Orthogonal Function (CEO). (b) Correlation between Large-scale Index for the South American Monsoon (LISAM) and Tropical Rainfall Measuring Mission (TRMM) precipitation.

Data Source: LISAM used Climate Forecast System Reanalysis (CFSR; Saha et al., 2010). Precipitation: TRMM (Huffman et al., 2007).

While the oceanic- and continental-SACZ can be observed independently (Carvalho et al., 2004; Carvalho, Jones, & Liebmann, 2002), eventually they may merge (Carvalho et al., 2011; Fialho et al., 2023), enhancing precipitation from southern Amazon to the western South Atlantic. Extreme precipitation and floods have been associated with both the oceanic- and continental-SACZ (Carvalho et al., 2004; Carvalho, Jones, & Liebmann, 2002; Pezzi et al., 2023). The SACZ (continental or oceanic) is characterized by enhanced precipitation on its equatorward side and suppressed rainfall on its poleward side. Thus, the SACZ positioning and persistence are critical for water supply and disaster risk management over large populated areas of SESA.

Occasionally during summer, midlatitude wave trains with an equivalent barotropic structure propagate equatorward following a wave path along the western South Atlantic (Hoskins & Ambrizzi, 1993; Liebmann et al., 1999). These wave trains are responsible for the seesaw in circulation and convection that affects SESA and the oceanic-SACZ (Cunningham & Cavalcanti, 2006; Nogués-Paegle & Mo, 1997; Talento & Barreiro, 2018). When sea-surface temperatures favor the development of an extratropical cyclone next to the east coast of South America, westerly winds intensify over land and the continental-SACZ develops, enhancing precipitation from central Brazil to the subtropical western Atlantic for several days (Fialho et al., 2023). Additional discussions on the SACZ and the associated precipitation are provided in Liebmann and Bladé (2024).

The SAMS exhibits features commonly found in other monsoon systems (Reason, 2016; Rao et al., 2024). For example, precipitation patterns over the Amazon Basin and continental-SACZ are closely linked to the presence of an upper-tropospheric anticyclonic circulation known as the “Bolivian High” (Lenters & Cook, 1997). The Bolivian High is often accompanied by a trough to the east referred to as the “Nordeste Low.” When convection intensifies over the SAMS domain, this ridge-and-trough pair becomes well-defined—a response attributed to the release of latent heat (Marengo et al., 2010; Silva Dias et al., 1983; Vera, Higgins, et al., 2006).

The high elevation and long meridional extent of the Andes, from 10°N to 57°S, exert a significant influence on the hydroclimate of South America. Numerical experiments in which the Andean heights were progressively removed demonstrated that the cordillera plays a critical role in transporting moisture from the tropics to the subtropics of South America (Insel et al., 2010). The high elevations and north-south orientation of the Andes block the oceanic flow from the Pacific and deviate the westerly flow from the Atlantic and the Amazon toward central and subtropical South America. Convection on the eastern side of the Andes, including the SAMS domain, depends on this transport. Furthermore, the orographic lifting is responsible for the initiation and enhancement of deep mesoscale convective systems (Houze et al., 2015; Rasmussen & Houze, 2016; Romatschke & Houze, 2013).

One of the most relevant features that influences the SAMS is the frequent occurrence of northerly low-level jets on the eastern slopes of the Andes. These jets play a major role in the South American hydroclimate by acting as conduits of moisture across the continent. Jones et al. (2023) identified four types of low-level jets that affect precipitation patterns in South America. These jets manifest as synoptic-scale disturbances (lasting from hours to days) in the meridional winds of the lower-troposphere east of the Andes, with maximum intensity observed at distinct geographic locations. These low-level jets typically enhance during nighttime due to the collapse of the convective

boundary layer and exhibit variable spatial extent and duration. Jones et al. (2023) showed that their spatiotemporal variability is influenced by midlatitude Rossby wave trains propagating from the Pacific Ocean toward South America. In their path, these wave trains modulate pressure gradients and circulation over the continent. Eventually, the induced disturbances contribute to the acceleration of winds east of the Andes in the lower troposphere (around 850 hPa). This will happen at specific latitudes, depending on the position of the cyclones and anticyclones associated with the wave trains.

The most well documented low-level jet that affects the SAMS is typically observed east of the Bolivian Andes and is referred to as the “central Andes” jet (Jones et al., 2023) or more generically as the South America Low-Level Jet (Marengo et al., 2004; Montini et al., 2019; Vera, Baez, et al., 2006). The central Andes jet occurs year-round and is important for transporting moisture from the Amazon to La Plata Basin. It has been related to the formation of remarkably deep convective systems that can often reach the upper-troposphere and lower-stratosphere (Gamelin et al., 2022). At the jet’s exit region, mesoscale convective complexes can be formed, causing extreme precipitation events in La Plata Basin (Durkee & Mote, 2010; Salio et al., 2007). Consequently, when the central Andes jet is active, the SAMS weakens as the supply of moisture from the Amazon is depleted (Carvalho & Silva Dias, 2021).

The other important low-level jet is described in Jones et al. (2023) as the “northern jet.” This jet has been often referred to as the “Orinoco jet” (Builes-Jaramillo et al., 2022; Jiménez-Sánchez et al., 2019). The relevance of the northern jet to the SAMS is that it transports moisture away from Northwestern South America (Colombia, Orinoco Basin) toward tropical South America. Similar to the central Andes jet, the northern jet appears related to a phase of a propagating Rossby wave train that favors cross-equatorial northerly winds across the Amazon and southerly winds east of the central Andes at 850 hPa (Jones et al., 2023). Interestingly, there is evidence that this same phase encourages the development of the oceanic-SACZ.

The Seasonal Cycle of the SAMS

What distinguishes the SAMS from other monsoon systems is the absence of seasonal reversal in circulation. The existence of a monsoon system in South America (SA) was only recognized after the study by Zhou and Lau (1998), which demonstrated that once the annual mean is removed, the seasonal cycle in circulation resembles those of other monsoon systems. Figure 2 illustrates the seasonal cycle of the SAMS by showing monthly 850 hPa wind anomalies (annual mean removed) and precipitation.

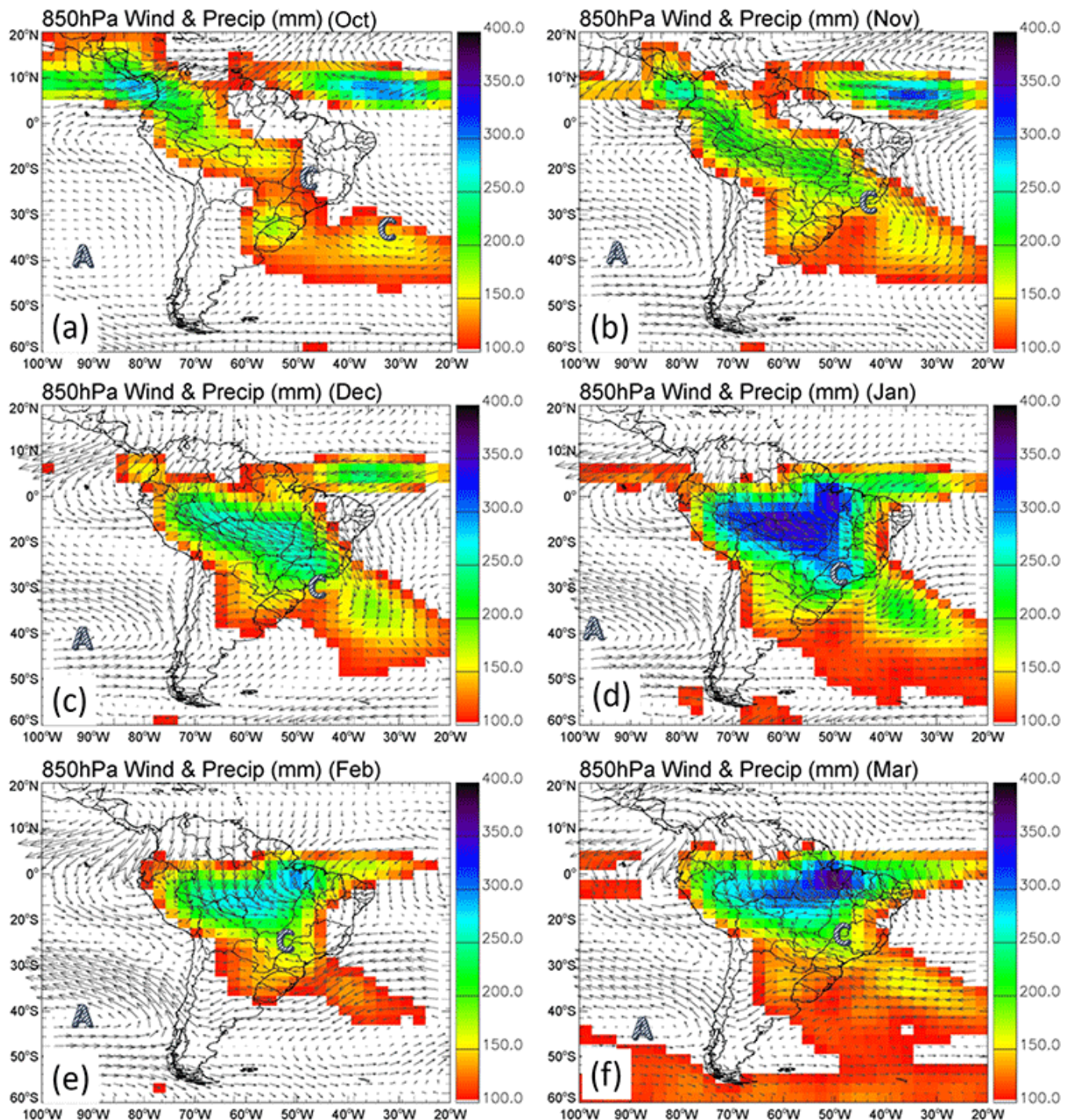


Figure 2. The SAMS monthly average precipitation (mm) and 850 hPa wind anomalies (annual mean removed). Months (October to March) are indicated at the top of each frame. Symbol “C” indicates centers with cyclonic anomaly whereas “A” indicates anticyclonic anomaly.

Data Source: Precipitation from Global Precipitation Climatology Project (GPCP; Huffman et al., 1997); 850 hPa winds are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al., 2018).

By October (Figure 2a), with increasing solar radiation in the Southern Hemisphere, a cyclonic anomaly begins to develop over eastern tropical SA centered at approximately 20°S, 50°W. This cyclonic anomaly increases the transport of moisture from western Amazon toward central Brazil. Another cyclonic anomaly, centered approximately at 35°S, 30°W over southwestern Atlantic, further contributes to the increase in moisture transport from the equatorial to the subtropical South Atlantic. The resulting low-troposphere westerly anomalies increase the transport of moisture across the Amazon, and soil-moisture feedbacks contribute to maintaining the convective activity over the continent (Chen & Dominguez, 2024; Collini et al., 2008; Giles et al., 2023; Li & Fu, 2004).

By November (Figure 2b), a cyclonic anomaly begins to develop over the coast of southeastern Brazil, playing a significant role in the development and maintenance of the continental-SACZ. Westerly wind anomalies are observed across most of tropical SA, while cross-equatorial flows increase over northwestern Amazon, contributing to a progressive increase in moisture transport to tropical SA (Wang & Fu, 2002). Concomitantly, the cross-equatorial northerly winds over tropical South Atlantic supply moisture for the development of the oceanic-SACZ.

A similar spatial pattern of circulation anomalies and precipitation is observed in December (Figure 2c), except that cross-equatorial flows intensify across the entire equatorial SA, leading to an increase in precipitation over tropical SA. The peak of the SAMS rainfall is observed in January (Figure 2d) when the northerly cross-equatorial wind anomalies are the strongest, transporting moisture from the Intertropical Convergence Zone to the continent. Evapotranspiration from local sources and moisture transport from remote regions are then intensified (Zemp et al., 2014). The corridor of lower-troposphere westerly winds turns into a critical conduit for transporting moisture from the Amazon and the Equatorial Atlantic across tropical South America, leading to enhanced precipitation in the SAMS domain. Latent heat released by the enhanced precipitation is likely responsible for the shift of the cyclonic anomaly toward southeastern Brazil. Conversely, easterly wind anomalies increase over the western tropical South Atlantic. Enhanced evaporation from the tropical South Atlantic may contribute as a source of moisture for the development and maintenance of the oceanic-SACZ when synoptic conditions are favorable for the equatorward propagation of a midlatitude wave train (Fialho et al., 2023).

The increase in rainfall and cloudiness during the peak of the summer (December–January) has significant implications for the monsoon cycle. Some studies suggest that both increased cloudiness and precipitation may lead to negative feedback in the monsoon by cooling and stabilizing the lower troposphere (e.g., Grimm & Zilli, 2009). As a result, the region experiencing maximum precipitation and convergence would shift toward neighboring areas that previously had suppressed convection. Convection begins to shift equatorward in February (Figure 2e) and by March (Figure 2f), a zonally oriented band of precipitation and convergence starts developing in the low latitudes of SA (north of 10°N). After April, a progressive return of convection to the northern hemisphere becomes evident (Grantz et al., 2007).

The seasonal cycles of precipitation and circulation highlight some unique features of the SAMS. Notably, the low-level cyclonic anomaly that forms during the monsoon season is not connected to the long, narrow low-pressure band east of the Andes, known as the “Northwestern Argentinean Low” and the “Chaco Low” (Arraut et al., 2023). Instead, the development of the SAMS is

accompanied by westerly winds in the lower troposphere that carry moisture from the Amazon across tropical South America (Carvalho et al., 2011). This is possible because of the development of a cyclonic anomaly at 850 hPa over southeastern Brazil (see Figure 2). This feature discourages the moisture transport from the Amazon to the subtropics.

The Active and Break Phases of the SAMS

Like other monsoon systems, the SAMS exhibits active and break phases on intraseasonal timescales characterized by enhanced and suppressed convection respectively. It has been shown that active periods are associated with an enhancement of the lower-troposphere westerly wind anomalies (westerly regime) over tropical South America, whereas easterly anomalies (easterly regime) dominate during break phases (Carvalho, Jones, & Silva Dias, 2002; Jones & Carvalho, 2002). Westerly wind anomalies in the lower troposphere, which are critical for the transport of moisture across tropical South America, play a critical role in the diurnal cycle of precipitation along the continental-SACZ (Herdies et al., 2002; Rickenbach et al., 2002). Easterly anomalies are associated with the westward shift of the South Atlantic anticyclone, along with changes in the characteristics of moist static energy, aerosols, and other physical properties.

Notably, active and break phases accompany important changes in the structural properties and geographic distribution of mesoscale convective systems (MCSs; Carvalho, Jones, & Silva Dias, 2002; Carvalho, Jones, et al., 2002; Petersen et al., 2002). For instance, Petersen et al. (2002) used remote sensing observations of precipitation and lightning during contrasting easterly and westerly anomalies in SA during the Large-Scale Biosphere–Atmosphere Amazonia (LBA) experiment (Avissar et al., 2002). They showed that lightning activity is more pronounced during easterly regimes over the southern Amazon and Mato Grosso, which is considered the core of the SAMS (Figure 1). Carvalho, Jones, and Silva Dias (2002) and Carvalho, Jones, et al. (2002) examined the diurnal cycle and structural properties of MCSs during the LBA campaign using infrared satellite images and a tracking technique (Carvalho & Jones, 2001) and identified a northwest–southeast dipole in precipitation and convective activity. During the SAMS active phase (westerly regime), precipitation increases over southeast Amazon and decreases over northwest South America, north of the equator (as displayed in Figure 1). A reversed pattern is observed during the SAMS break phase (easterly regime). Consistent with this observation, during the SAMS active phase, the frequency of MCSs increases toward eastern South America, and during the SAMS break phase, the frequency of deep convective systems increases over northwest Amazon (Carvalho, Jones, & Silva Dias, 2002).

Intraseasonal oscillations propagating across the Southern Hemisphere influence the SAMS's circulation and precipitation on subseasonal timescales. Midlatitude Rossby wave trains that propagate from the Pacific Ocean to the Atlantic Ocean are often linked to tropics–extratropics teleconnections associated with the eastward propagation of the Madden–Julian Oscillation (MJO; Madden & Julian, 1994). It has been shown that the MJO modulates extreme dry and wet events over the SAMS domain (Alvarez et al., 2016; Fialho et al., 2023; Grimm, 2019; Jones et al., 2004; Muza et al., 2009; Recalde–Coronel et al., 2020). The MJO phases that favor westerly winds over tropical South America are generally associated with an active SAMS, whereas phases that favor easterly

regimes are related to suppressed convection (Muza et al., 2009). However, the MJO is not the only mode associated with the subseasonal variability of the SAMS or the SACZ. More research is necessary to characterize these modes.

Climate Change in the SAMS

The anthropogenic warming of the planet since the 1970's has been rapid, and the Earth's climate system is adjusting to a new state of equilibrium. Each one of the features of the SAMS described in this article may be affected by this progressive warming, with unknown consequences. Additionally, the SAMS is influenced by teleconnections with coupled climatic modes on decadal-to-millennial timescales (Bahr et al., 2021; Cruz et al., 2009; Gamelin et al., 2020; Kayano et al., 2019) that have yet to be fully identified and understood. These modes may enhance or offset the response to the warming, adding further uncertainty to the future of the SAMS.

Global warming can significantly alter the intensity and distribution of rainfall over land and ocean. Some regions may experience increased precipitation, leading to more frequent and severe flooding, while others might face reduced rainfall and more frequent droughts. Additionally, the timing of monsoon onset and its duration could shift. For example, studies project a delay in the onset and an extension of the SAMS, potentially disrupting agricultural cycles and water resource management (Reboita et al., 2023).

Based on the Clausius–Clapeyron relationship, a warmer atmosphere has the capacity to hold higher water vapor saturation levels. As the planet warms, changes in stability profiles and other thermodynamic properties of the atmosphere are also anticipated. These changes can alter the hydroclimate leading to long periods of drought and enhanced evapotranspiration. When dynamic conditions conducive to storm formation arise in this altered environment, the intensity of extreme weather events—such as heavy rainfall and floods—may increase. These changes can significantly impact infrastructure, agriculture, and human settlements.

Zilli et al. (2017) analyzed daily precipitation data spanning the 5 to 7 decades (from mid-20th century to early 21st century) revealing compelling evidence of an increase in both the frequency and intensity of extreme events across many locations in populated areas in eastern Brazil. Notably, a systematic detection of increased extreme rainfall events has been well-documented across South America, as discussed by Carvalho (2019).

In a subsequent study, Pezzi et al. (2023) observed an unusual surge in oceanic–SACZ events during the summer of 2021–2022. These events led to extreme precipitation in coastal areas, a phenomenon amplified by the intricate and relatively steep topography of coastal Brazil. However, a critical question remains: Are these extreme precipitation events inherent to the natural variability of the oceanic–SACZ or are they exacerbated by anthropogenic warming of the ocean and the atmosphere? Further analyses are necessary to unravel this complex relationship.

The SAMS—which comprises the SACZ and the low-level jets—is influenced by teleconnections with climatic modes such as the El Niño–Southern Oscillation (ENSO; Ambrizzi et al., 2004; Fernandes & Grimm, 2023), the Pacific Decadal Oscillation (PDO; Garcia & Kayano, 2015; Silva et al.,

2020), the South Atlantic Dipole (Bombardi & Carvalho, 2011; Bombardi et al., 2014), the Atlantic Multidecadal Oscillation (Ceron et al., 2020; Chiessi et al., 2009; Jones, 2019; Jones & Carvalho, 2018), among others. However, evaluating teleconnections with low-frequency coupled modes poses a challenge due to the relatively short historical data records available for South America. Furthermore, global warming may introduce modifications to these teleconnection patterns, affecting their interactions with the SAMS. This, in turn, impacts critical aspects such as the onset and demise of the monsoon and the spatiotemporal distribution and intensity of rainfall.

Mechanisms associated with low-level jets may also be affected by global warming. These changes can influence the distribution of moisture across the continent, impacting regions in various ways. For example, changes in frequency and intensity of the central Andes jet will affect the SAMS precipitation and the frequency of mesoscale convective complexes in La Plata Basin. Conversely, alterations in the frequency and intensity of the Orinoco jet may influence the transport of moisture to the Amazon and the SACZ. While Jones et al. (2023) have not detected any significant trend in the annual frequency of low-level jets affecting South America during the extended summer season (October–March) from 1979–2021, they did establish a strong relationship between these jets and ENSO phases. Mu et al. (2024) investigated the variability of low-level jets using 65 years of reanalysis and showed that the central Andes jet, which increases precipitation over La Plata Basin, prevails during El Niño years that occur within the warm and neutral PDO phases. Conversely, the northern (Orinoco) jet, which enhances moisture in the SAMS domain, prevails during La Niña years that occur within the cold PDO phase. If ENSO characteristics change over time, either by natural variability, anthropogenic climate change, or a combination of both, one should expect impacts on the jets and, consequently, on South America's hydroclimate.

Notably, several studies have demonstrated links between ENSO characteristics—and respective teleconnections with the Southern Hemisphere—and the PDO. For example, Gamelin et al. (2020) revealed that Rossby wave trains across South America associated with El Niño during the peak of the monsoon season (December–February) alter their spatial characteristics and pattern of propagation depending on the PDO phase. These wave trains influence circulation from the troposphere to the lower-stratosphere over tropical and subtropical South America.

Quantifying changes in the behavior of the SAMS with instrumental records is challenging for many reasons. The SAMS core is primarily located in central tropical South America, where maintaining a reliable network of in situ observations is difficult (Fu et al., 2013). Rain gauges are scarce, and many records have been discontinued. Although precipitation estimates from satellites in recent decades improved the spatial coverage capability, these products are often calibrated based on these sparse and temporally discontinued gauged rainfall, limiting studies on rainfall trends and particularly on trends of daily extreme events at the core of the SAMS (Carvalho, 2019).

Despite these limitations, several studies have indicated significant changes in the SAMS. Fu et al. (2013) observed a decrease in local convective energy during the austral winter (June–August) due to a decline in available moisture sources. They hypothesized that this decline led to an extended dry season (September–November) in southern Amazonia between 1979 and 2011.

Sena et al. (2018) investigated the onset and duration of the rainy season in the Brazilian Amazon Basin using geostationary satellite datasets from 1987 to 2009. They showed evidence that the fraction of cloudiness has decreased over the region throughout the period, primarily attributed to high clouds. Additionally, they inferred a shortening of the rainy season by approximately 21 days, consistent with the Fu et al. (2013) study. While definite attributions remain elusive, Smyth and Ming (2020) suggested that the steady increase in sea surface temperatures is likely responsible for the drying of the SAMS precipitation from September to November.

Intensive deforestation of the Amazon rainforest and neighboring areas may already be impacting the precipitation cycle of the SAMS in the present climate (Bochow & Boers, 2023). One potential consequence of massive deforestation is an alteration of the biosphere–atmosphere coupling dynamics. Moreover, subsidence appears to have increased over central South America in the winter and much of the spring since the early 2000s. These changes may have resulted from a combination of natural variability and anthropogenic climate change. Together, these processes could be contributing to the lengthening of the dry season and the emergence of extensive drought conditions. These conditions, in turn, can further increase deforestation by encouraging more fires, creating a feedback loop that impacts the SAMS (Bochow & Boers, 2023; Espinoza et al., 2021). However, the precise effects of deforestation and land-use change on the atmospheric circulation patterns and the full extent of these impacts—from meso-to-large-scales—remain open questions.

Remarkably, Stríkis et al. (2024) used geochemical proxies in speleothems from a cave located in central-eastern Brazil and revealed what they termed as “a severe warming trend,” which began in the 1970s. Their study indicates that the aridity observed in the second decade of the 21st century is unparalleled in the last 720 years. While a climate shift in the early 1970s may have affected precipitation patterns in SA (Carvalho et al., 2011; Coper & Garreaud, 2015; Stríkis et al., 2024), attribution analysis suggests that this severe prolonged drought cannot be solely attributed to natural climate variability. Instead, there appears to be a strong association with the increased emission of greenhouse gases.

Additionally, there is compelling evidence that the SACZ has undergone significant changes in the first two decades of the 21st century. Zilli et al. (2019), using reanalyses and outgoing long-wave radiation, demonstrated that the SACZ has shifted poleward in the first 2 decades of the 21st century. These results increase the confidence in the observed and projected drying trends over eastern Brazil, corroborating with the paleoclimatic study of Stríkis et al. (2024). In a subsequent study, Zilli and Carvalho (2021) assessed the relative contribution of natural variability and anthropogenic forcing to the observed poleward shift of the SACZ during the historical period using 20 global climate models participating in the fifth phase of the Coupled Model Intercomparison Project. Most models underestimate the magnitude of the observed trends and a few misrepresent the observed signal of the trend and spatial variability. Interestingly, despite the large discrepancies among models, the attribution analysis for the most realistic models suggests that precipitation trends could partially result from land-use change, followed by change in ozone concentrations. Additional discussions on climate change and the SACZ are provided in Liebmann and Bladé (2024).

Reasonably, one can assume that anthropogenic climate change is amplifying the dryness of the SAMS, and if this “business as usual” scenario continues, it could lead to an unhealthy rainy season in the future.

The Anthropogenic Climate Change Impacts on the SAMS Cycle

How to assess the impacts of human actions on the climate? Global climate models (GCMs) serve as essential tools for projecting future climate scenarios. These models are employed by research institutions worldwide, often as part of a comprehensive initiative known as the Coupled Model Intercomparison Project (CMIP).

In short, the CMIP's objective is to enhance the understanding of climate changes—both historical and projected—resulting from natural variability or in response to changes in radiative forcing. By comparing multiple models and scenarios, it is possible to gain insights into the complex interactions within the Earth's climate system.

In 1980, the World Climate Research Programme (WCRP) was established with a critical mission: to explore how far into the future one can predict global climate changes and understand the influence of human activities on the climate (WCRP Joint Scientific Committee, 2019). With this purpose, the WCRP has been committed to support climate science, providing valuable information to stakeholders and policymakers worldwide.

In 1995, under the guidance of the WCRP Working Group on Coupled Modeling, the CMIP project set sail. Its primary goal was to delve into the impacts of human-induced forcings on climate change by utilizing sophisticated GCMs.

Driven by historical and future idealized forcings, the CMIP GCMs simulate potential climate outcomes far into the future. These models explore scenarios with various concentrations of greenhouse gases (GHGs) to project how the climate might evolve. Notably, CMIP has undergone several phases, including CMIP3, CMIP5, and CMIP6.

- **CMIP3:** Conducted in 2007, CMIP3 employed specific emissions and concentration-driven scenarios. Its results have significantly contributed to the scientific basis for the Intergovernmental Panel on Climate Change (IPCC) reports.
- **CMIP5:** Launched in 2009, CMIP5 continued this effort, refining the understanding of climate change impacts. Researchers used updated models and scenarios to assess potential futures.
- **CMIP6:** Initiated in 2016, CMIP6 builds upon its predecessors. CMIP6 models incorporate improved physics, higher spatial resolution, and more comprehensive representations of Earth system components.

These CMIP phases serve as critical tools for policymakers, providing essential information about climate change. Regional climate models are then utilized to investigate specific regions of the world. These models downscale the CMIP results, allowing a better assessment of local impacts. Christensen and Christensen (2007), Giorgi et al. (2008), and Mearns et al. (2009) have contributed significantly to this field by examining climate change effects on specific parts of the world.

The 2023 summary of climate change impacts on key climate reference regions (CRRs) in Central America (CA) and SA—the IPCC Sixth Assessment Report (AR6)—stated that there is high confidence in the onset delay and low confidence in the precipitation projected changes in the SAMS throughout the 21st century (Castellanos et al., 2022). Figure 3a displays eight CRRs in CA and SA based on Iturbide et al. (2020).

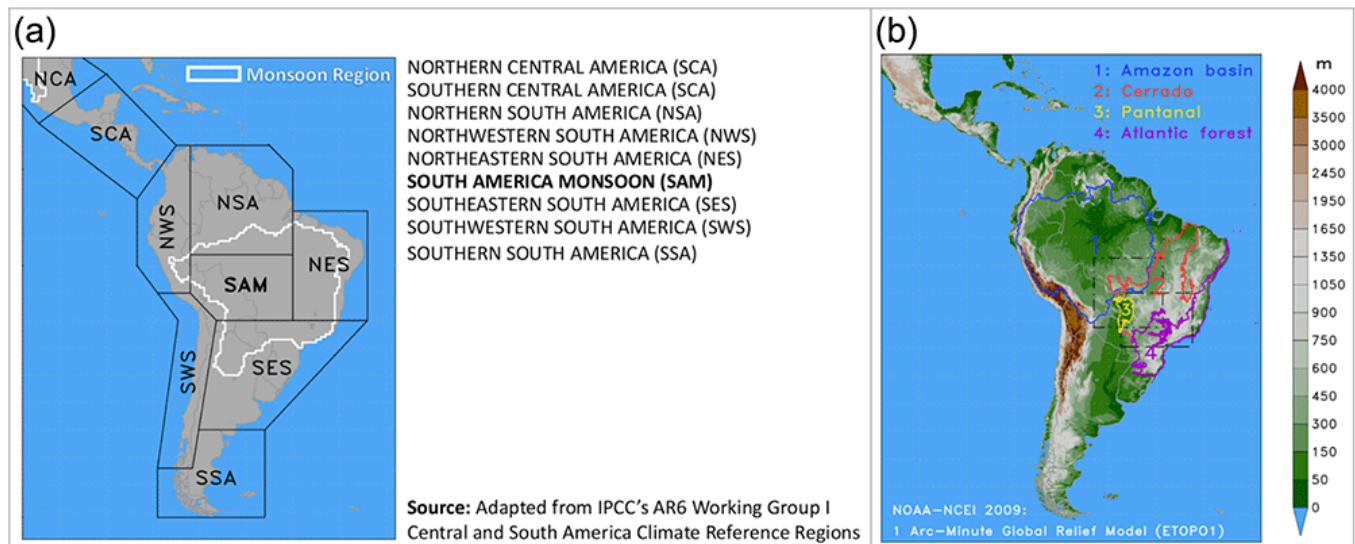


Figure 3. (a) IPCC's climate reference regions (Iturbide et al., 2020) for Central and South America; (b) the ETOPO1 elevation (in meters), and delimitations of the Amazon River Basin (1: dark blue) and the Cerrado (2: red), Pantanal (3: yellow), and Atlantic Forest (4: purple) biomes. White contours show the North and South American monsoon regions in (a), dot-dashed and dashed lines delimit SAMS-1 and SAMS-2 regions in (b) respectively.

Data Source: National Oceanic and Atmospheric Administration (NOAA)–National Centers for Environmental Information (NCEI), 2009.

Notably, these CRRs create some artificial boundaries that arbitrarily separate the contributions of the main features of the SAMS (see Figures 1 and 2). For example, the core of the SAMS in the CRR “SAM” is separated from the continental- and oceanic-SACZ and excludes the area over southeastern Brazil where significant changes in precipitation are observed throughout the rainy season (Figure 2). The SACZ contribution splits between the “NES” and the “SES” domains. The “SES” domain extends over a region where the seesaw in precipitation associated with the oceanic-SACZ is climatologically observed (Figure 1). The “NES” includes the climatological SACZ and the semiarid region of Brazil—which is influenced by the Intertropical Convergence Zone—in the same domain. The mix in precipitation regimes and the arbitrary boundaries of the domains need to be carefully evaluated when projecting future changes in precipitation.

Gomes et al. (2022) divided the Amazon and La Plata River Basins (AMB and LPB respectively) into the northern (NAMB and NLPB) and southern (SAMB and SLPB) domains. In their work, SAMB encompasses portions of SAM, whereas the southern boundary of the NLPB includes parts of the northern SES domain displayed in Figure 3a. Using three CMIP5 National Oceanic and Atmospheric Administration–Geophysical Fluid Dynamics Laboratory (NOAA–GFDL) climate models, their

study found a delayed onset of the SAMB and NLPB monsoon-like rainy seasons at the end of the 21st century. In that assessment, they used the most extreme trajectory among the Representative Concentration Pathways–RCP 8.5, which is the RCP without any stabilization of GHGs by the end of the 21st century (Moss et al., 2010).

To further address the sensitivity of the projected climate change to the chosen domain, the SAMS was divided into two distinct regions, named SAMS-1 and SAMS-2. These two domains encompass the most convective region over SA during the wet season (see Figure 1). SAMS-1 is centered in the core of SA (marked by dot-dashed lines) and encompasses the region with the highest correlation between precipitation and the SAMS index described in Silva and Carvalho (2007), as shown in Figure 1. SAMS-2 lies further to the southeast (indicated by dashed lines) and is closely correlated with the SACZ. These two domains discern changes in the SAMS's water cycle that directly impact critical biomes such as the Amazon River Basin (1: represented by a dark blue contour); the Brazilian Savanna—Cerrado (2: depicted with a red contour); the Pantanal (3: highlighted in yellow); and the Atlantic rainforest (4: outlined in purple; see Figure 3b).

The number of available stations (rain gauges) from the Global Precipitation Climatology Centre (GPCC) version 2022 (GPCCv2022) for the domains SAMS-1 and SAMS-2 is displayed in Figure 4. GPCCv2022 is a new centennial gridded dataset reprocessed at 0.25°, 0.5°, 1.0°, and 2.5° resolutions (Table 1). Figure 4 shows GPCCv2022 at a coarser resolution for clarity. Note that SAMS-1 (Figure 4a, b, e, and f) and SAMS-2 (Figure 4c, d, g, and h) have different number of stations contributing to the gridded precipitation product.

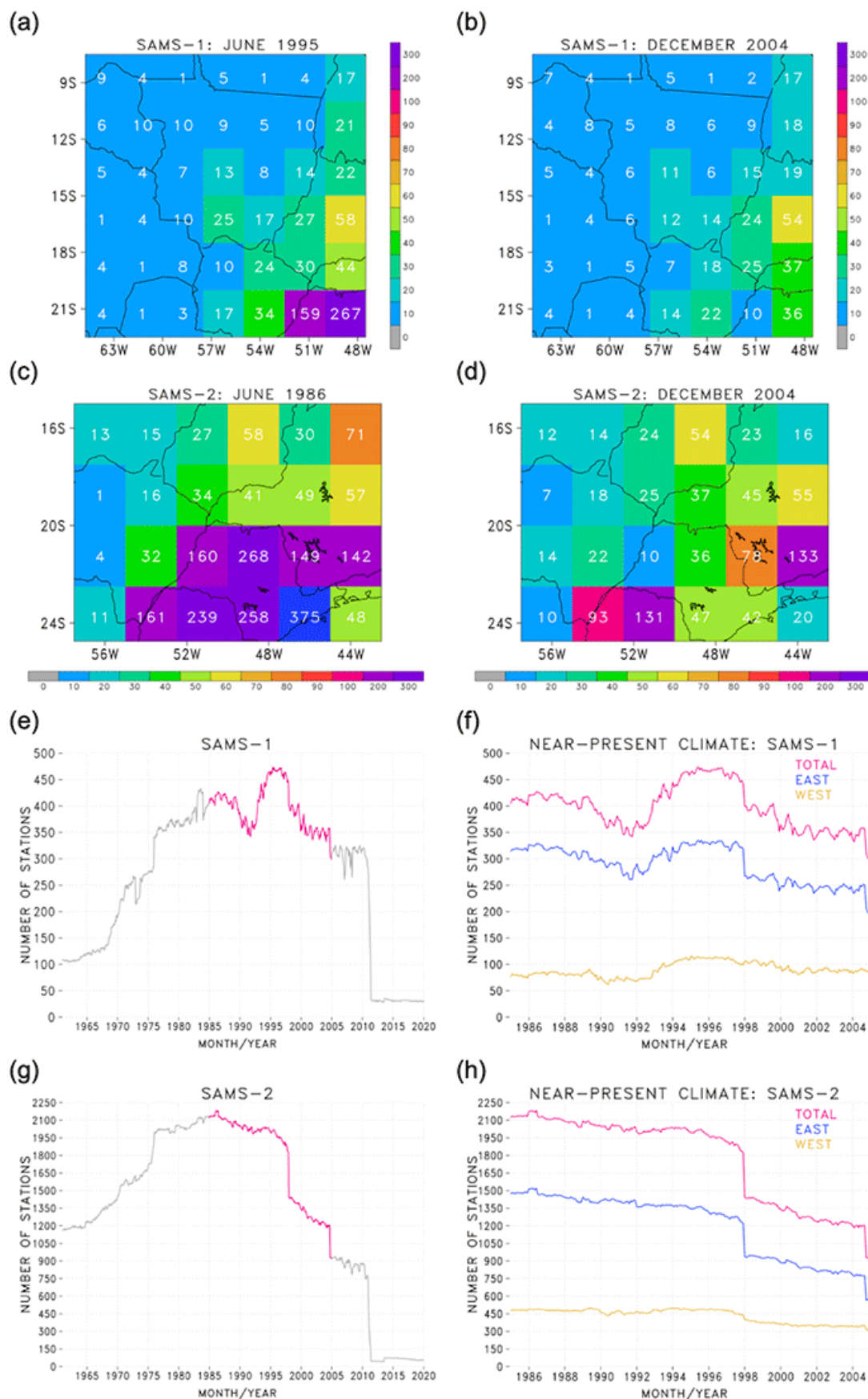


Figure 4. Number of stations (rain gauges) in each grid cell (color bar indicates the intervals) for the months with the maximum and minimum number of rain gauges in (a–b) SAMS-1 and (c–d) SAMS-2 respectively. The gray curves display the available stations from January 1961 through December 2020 in the SAMS-1 (e) and SAMS-2 (g) areas; the portion in magenta marks the near-present period from January 1985 to December 2004. The blue and dark yellow lines indicate the number of available gauges in the near-present on the eastern and western sides of SAMS-1 (f) and SAMS-2 (h) respectively.

Data Source: GPCCv2022.

Table 1. Reference Datasets Used in This Article

Name	Horizontal Resolution (Lat × Lon)	Variable Source	Country	Data Reference
Climate Hazards Group InfraRed Precipitation with Station data Version 2 (CHIRPS-2.0) ¹	0.05° × 0.05°	Satellite + gauge	United States	Funk et al. (2015)
European Centre for Medium-Range Weather Forecasts ² Fifth Generation Reanalysis (ERA5)	0.25° × 0.25°	Atmospheric Model ³	United Kingdom	Hersbach et al. (2020)
Global Precipitation Climatology Centre Version 2022 ⁴ (GPCCv2022)	2.5° × 2.5° 0.25° × 0.25°	Gauge	Germany	Schneider et al. (2022a, 2022b)

¹ CHIRPS-2.0 monthly means were obtained from CHIRPS: Rainfall Estimates from Raingauges and Satellite | Climate Hazard Center, UCSB <https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_monthly/netcdf>.

² European Centre for Medium-Range Weather Forecasts (ECMWF) is an intergovernmental organization supported by European countries with its headquarters in Reading, United Kingdom.

³ ERA5 precipitation is model-based from parameterizations, and its monthly means were obtained from Copernicus Climate Change Service Climate Data Store (Hersbach et al., 2023).

⁴ GPCCv2022's 2.5-degree gauge density and 0.25-degree precipitation datasets were obtained from Global Precipitation Climatology Center, NOAA Physical Science Lab <https://opendata.dwd.de/climate_environment/GPCC/full_data_monthly_v2022/25>

From the late 1970s to the first decade of the 21st century, the number of stations in SAMS-1 increased from about 300 to around 450. In contrast, SAMS-2 encompasses some of the major metropolitan areas in Brazil. Consequently, it has a higher density of stations compared to SAMS-1 in most of the GPCCv2022 grid cells (Figure 4c, d). The number of stations in SAMS-2 increased from about 1,950 in 1965 to over 2,100 around the year 2000 (Figure 4g, h), but significantly dropped after the year 2010. The largest concentration of stations has been observed on the eastern side of the SAMS-2 domain. Therefore, the period from roughly 1997 to 2020 was not very promising in terms of station counts (Figure 4e–h), even after considering a latency period of 5 years to update stations in the GPCCv2022 product. The sharp drop in the number of stations in both datasets may result in discontinuities that can compromise climate change studies in the SAMS using gauged precipitation. Considering the availability of stations and to provide a more reliable representation of the hydroclimate in both regions, the analyses presented in this article for the historical period are carried out across the “near-present,” extending from January 1985 to December 2004 (in magenta, Figure 4e–h).

The analysis of the “near-present” (hereafter “present”) was performed with the following precipitation datasets: GPCCv2022, the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), and the fifth generation of the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA5; see details in Table 1).

To assess changes in the precipitation annual cycle in the two regions, the authors discuss results from the latest CMIP6 models. For this purpose, they use future scenarios obtained from the Scenario Model Intercomparison Project (ScenarioMIP; Eyring et al., 2016; O’Neill et al., 2016). Four of the Shared Socioeconomic Pathways (SSPs; Eyring et al., 2016)—SSP1-2.6 (SSP126), SSP2-4.5 (SSP245), SSP3-7.0 (SSP370), and SSP5-8.5 (SSP585)—drove the three CMIP6 global models used in this article. SSPs are considered an update from the CMIP5 RCPs, the latter described in Moss et al. (2010), except for SSP370, which is a “gap-filling scenario” more likely to happen than SSP585. The order ranges from a sustainable and “greener” pathway to a global “fossil-fueled” society. The mean seasonal cycle of the three CMIP6 Earth System Models (ESMs—model names are detailed in Table-2) are examined in each one of the domains (Figure 5): GFDL-ESM4 (magenta), MPI-ESM1 (dark yellow), and MRI-ESM2 (dark blue). The ESMs offer a complex representation of the Earth system, including physical, chemical, and biological processes. Results from CMIP6 were also compared to precipitation datasets during the historical period when observations are available.

Table 2. Brief Description of the Three CMIP6 ESMs¹ Used in This Article

Institution-ESM#	Horizontal Resolution (Lat × Lon)	Variant Label ²	Country	Data or Model Reference
GFDL-ESM4 ³	1.3° × 1.0°	<i>r1i1p1f1</i>	United States	Krasting et al. (2018)
MPI-ESM1.2-HR ⁴	0.9° × 0.9°	<i>r1i1p1f1</i>	Germany	Müller et al. (2018)
MRI-ESM2.0 ⁵	1.1° × 1.1°	<i>r1i1p1f1</i>	Japan	Yukimoto et al. (2019)

¹ Earth System Grid Federation (ESGF) provided the free access to the CMIP6 ESM outputs.

² Model realization (*r*), initialization method (*i*), physics (*p*), and forcing (*f*).

³ Geophysical Fluid Dynamics Laboratory–Earth System Model version 4.

⁴ Max Plank Institute–Earth System Model version 1.2 High Resolution.

⁵ Meteorological Research Institute–Earth System Model version 2.0.

Figures 5 and 6 display the annual cycle of precipitation (mm/day) in SAMS-1 and SAMS-2 respectively. Although both regions present monsoon-like precipitation regimes, SAMS-1 exhibits the largest amplitude of the precipitation annual cycle, corroborating with the hypothesis that SAMS-1 captures the core of the monsoon. In Figures 5a and 6a, GPCCv2022 (light blue), CHIRPS (blue), and ERA5 (dark purple) are considered the “reference datasets.”

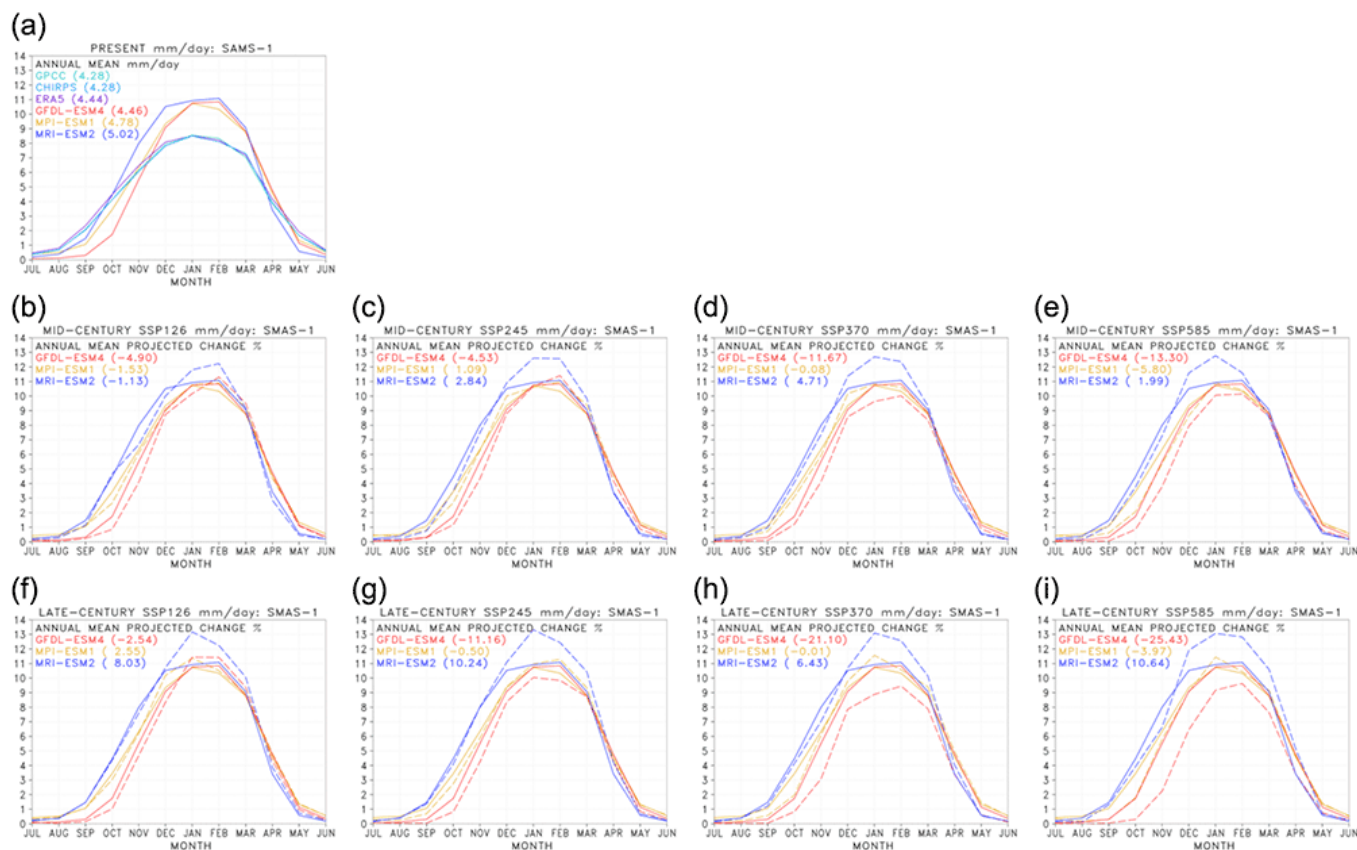


Figure 5. Annual cycle of precipitation in mm/day for the periods: (a) present (1985–2004), (b–e) midcentury (2041–2060), and (f–i) late-century (2081–2100). Panel (a) displays the reference datasets, GPCC (light blue), CHIRPS (blue), and ERA5 (purple), together with three ESMs. Solid lines and dashed lines indicate the present and future periods respectively for all three ESMs (b–i), specifically GFDL-ESM4 (red), MPI-ESM1 (dark yellow), and MRI-ESM2 (dark blue). The CMIP6 SSPs—SSP126 (b, f), SSP245 (c, g), SSP370 (d, h), and SSP585 (e, i)—drove the ESMs’ future climate. The relative change in projected annual means with respect to the present (%) are indicated within parentheses in each frame (b–i). All computations are calculated for the SAMS-1 domain.

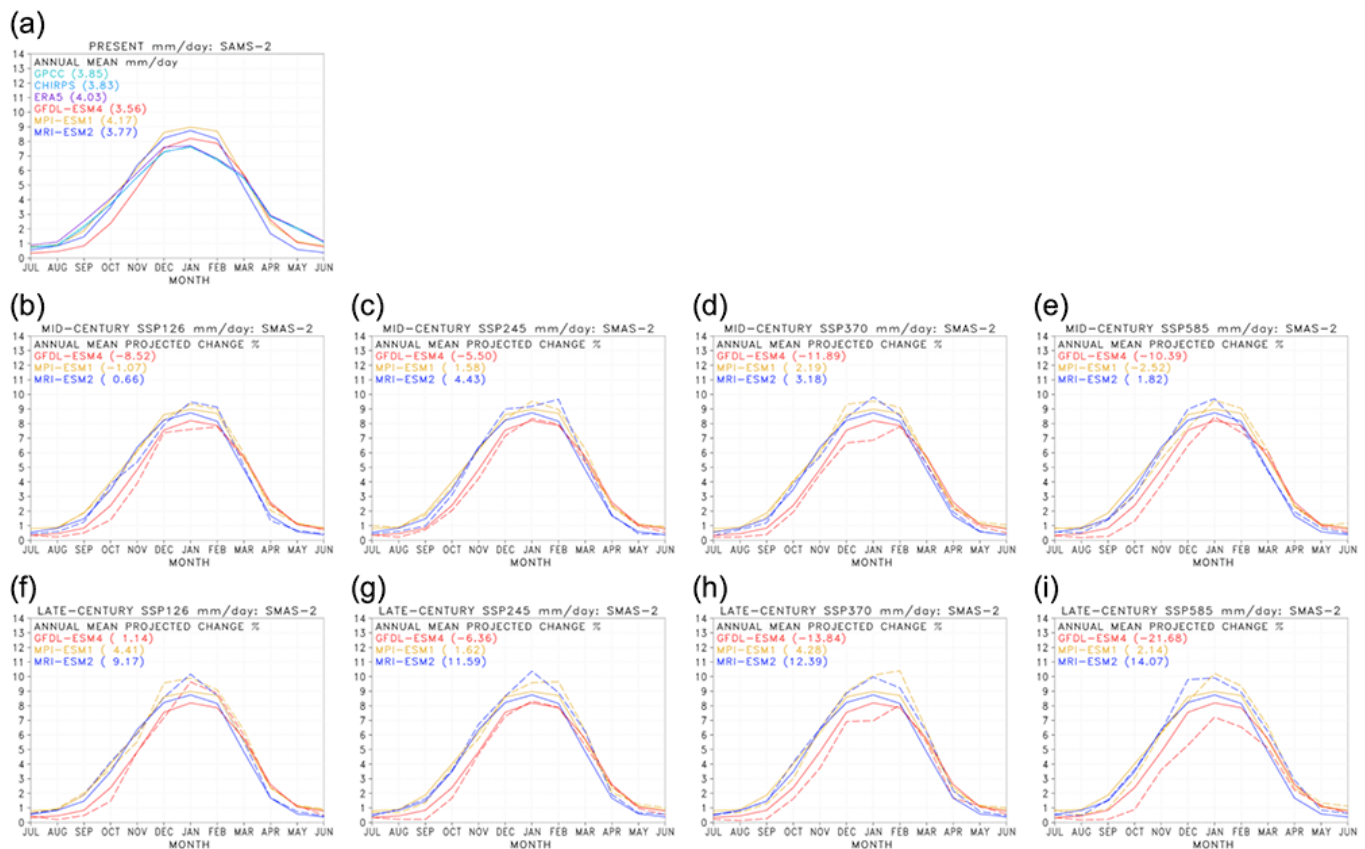


Figure 6. Same as in Figure 5, except for SAMS-2.

The reference data are closer to each other in the 20-year near-present period (Figures 5a and 6a). Notably, there are some discrepancies among model's seasonal cycles and between climate models and observations. For example, ESMs show a positive bias in the austral summer precipitation in comparison to the reference datasets. At the monsoon core, the ESMs indicate what might be considered a delayed onset of the monsoon in comparison to the reference datasets (Figure 5a). Among all ESMs, GFDL-ESM4 has the latest onset and is the driest model (see annual means), whereas MRI-ESM2 is the wettest. MPI-ESM1 stays in the middle in comparison to the other two ESMs.

Figures 5 and 6 also exhibit the annual cycle of the ESMs in the midcentury (2041–2060; Figures 5b–e and 6b–e) and late-century periods (2081–2100; Figures 5f–i and 6f–i). SAMS-1 presents significant changes in precipitation in the late-century period under SSP370 and SSP585, but the signals are not the same for all models. For example, GFDL-ESM4 indicates a reduction in the annual precipitation, regardless of the region. Conversely, MRI-ESM2 suggests an increase in the monsoonal precipitation in both regions.

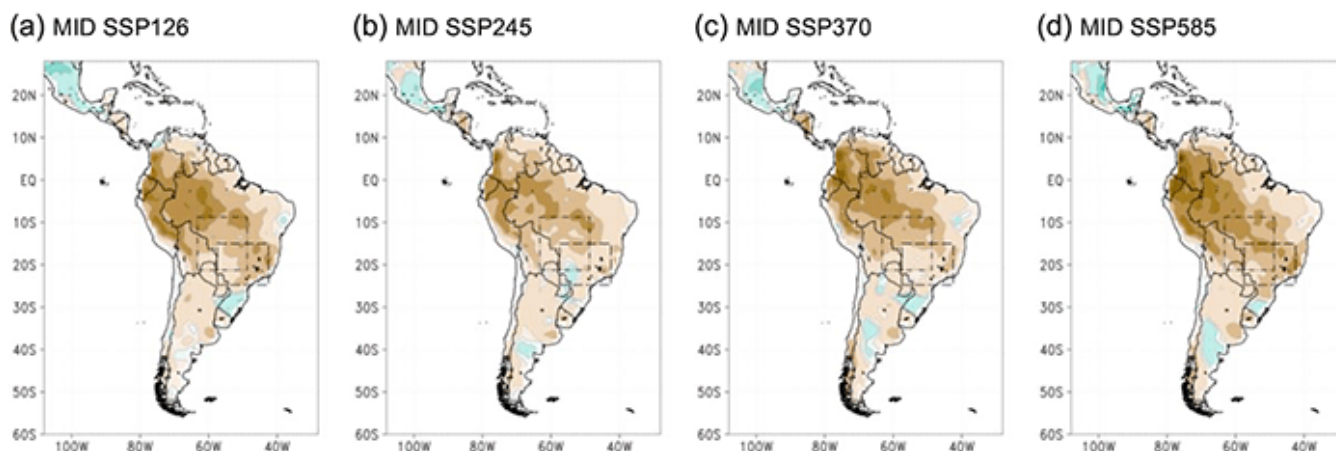
Differences in the onset and of the monsoon were also detected. For example, GFDL-ESM4 shows a reduction in precipitation early in the monsoon season in both SAMS regions (Figures 5 and 6), which could be an indication of a later onset. It projects a decrease in the precipitation annual mean of about 25% under SSP585 in the SAMS-1 late-century period. MPI-ESM1 seems to mostly agree with GFDL-ESM4 in the SAMS-1 and SAMS-2 late-century periods under more extreme scenarios.

In the midcentury period, MPI-ESM1 presents the most delayed onset under SSP585 in SAMS-1. MRI-ESM 2 shows a reduction in precipitation later in the pre-monsoon months in the SAMS-1 and SAMS-2 during late-century periods under SSP370 and SSP585. MRI-ESM2 indicates the highest increase in precipitation at the peak of the monsoon (between December–February). It offsets any earlier reductions in the year and increases the annual mean up to 14% in the late-century period under SSP585 in SAMS-2, except for a reduction under SSP126 from November to December in the midcentury period in SAMS-1 (the only reduction in the annual mean found in MRI-ESM2). Even though this study used only three ESMs, the chosen models reproduce the late onset discussed in AR6, despite differences in the SAMS domains utilized in that report.

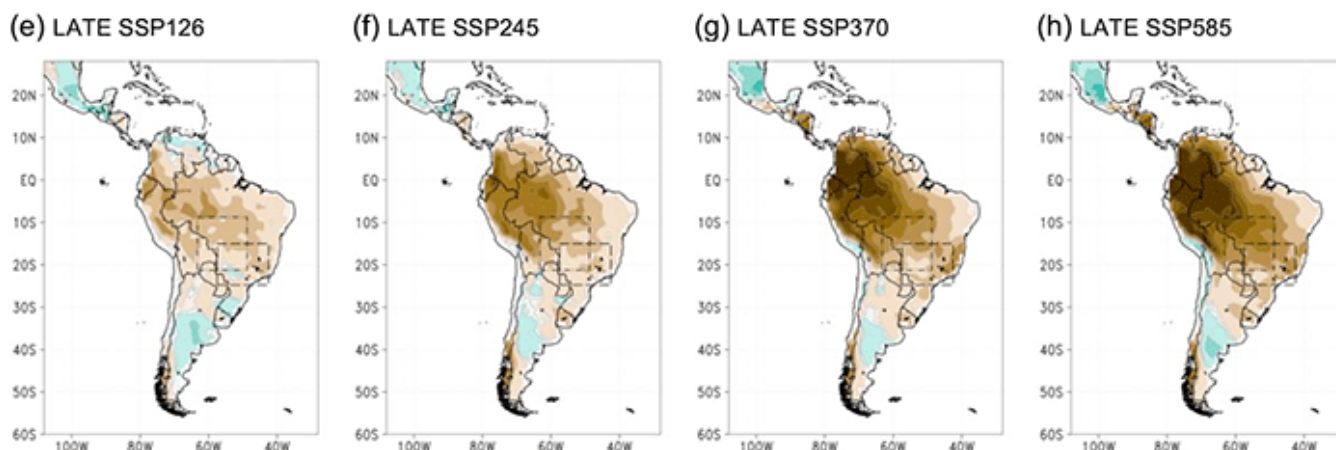
To further examine whether the onset of the SAMS will be delayed due to anthropogenic climate change, the authors investigated the projected changes in precipitation during pre-monsoon months (September–November). Results from GFDL-ESM4, MPI-ESM1, and MRI-ESM2 are illustrated in Figures 8–9 respectively. The pre-monsoon season is characterized by a progressive increase in daily precipitation, as exemplified by the Large-scale Index for the South American Monsoon-1 in Figure 1 (see discussion in Silva & Carvalho, 2007). Extended dry conditions during early summer months, when hydric stress reaches its maximum, have significant impacts on ecosystem health and agriculture. Additionally, the delay may also encourage a longer season with significant biomass burning and aerosol emissions that feedback on the SAMS by altering cloud properties and precipitation patterns, potentially leading to a late establishment of the monsoon season (Thornhill et al., 2018).

GFDL-ESM4

MID-CENTURY w.r.t. PRESENT: September to November



LATE-CENTURY w.r.t. PRESENT: September to November



ΔP mm/day

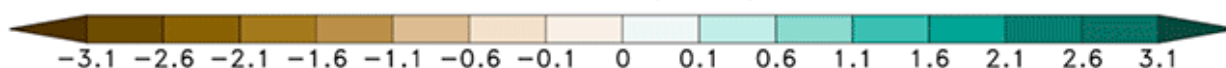
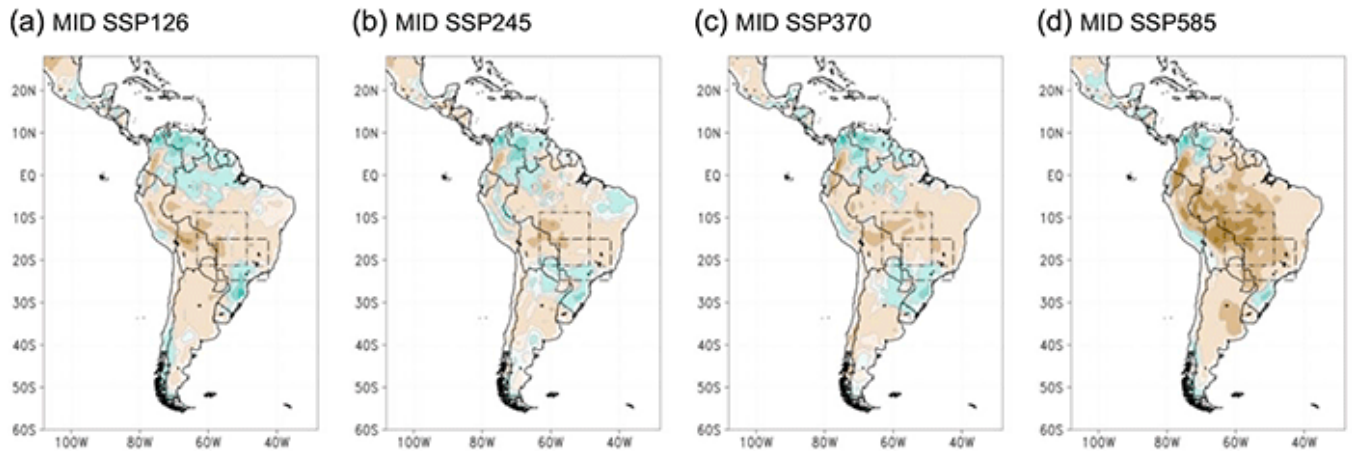


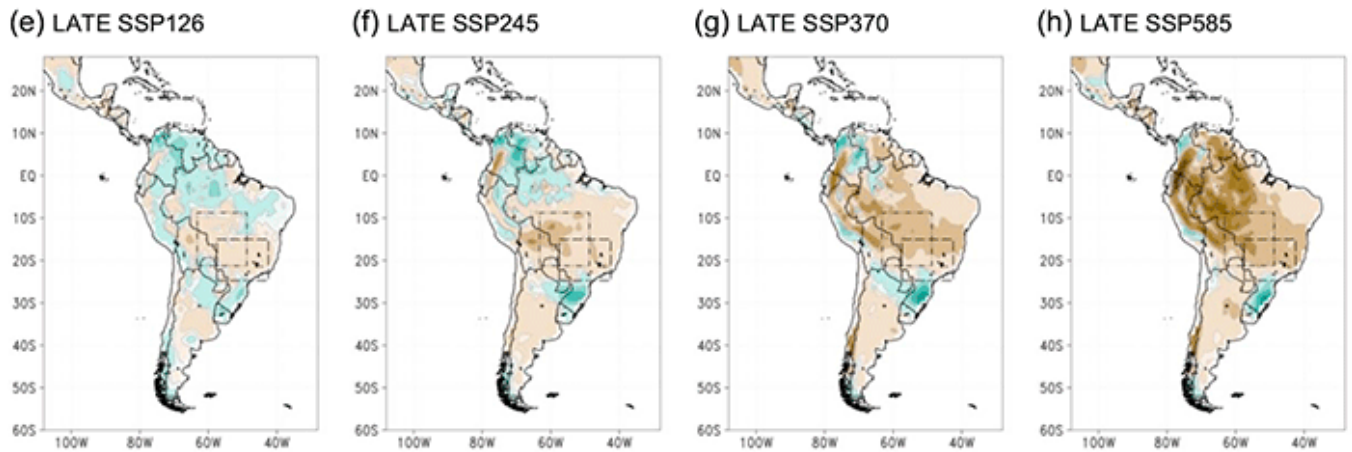
Figure 7. Projected changes in precipitation (ΔP , mm/day; September–November) for the midcentury (a–d) and late-century (e–h) periods with respect to the present climate. The CMIP6 SSPs—SSP126 (a, e), SSP245 (b, f), SSP370 (c, g), and SSP585 (d, h)—drove the GFDL-ESM4 future climate. Dot-dashed and dashed boxes delimit SAMS-1 and SAMS-2 respectively in all panels.

MPI-ESM1

MID-CENTURY w.r.t. PRESENT: September to November



LATE-CENTURY w.r.t. PRESENT: September to November



ΔP mm/day

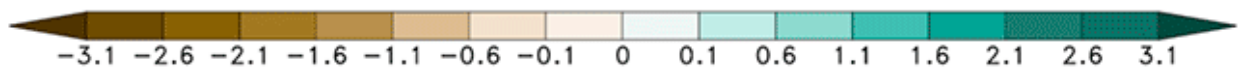
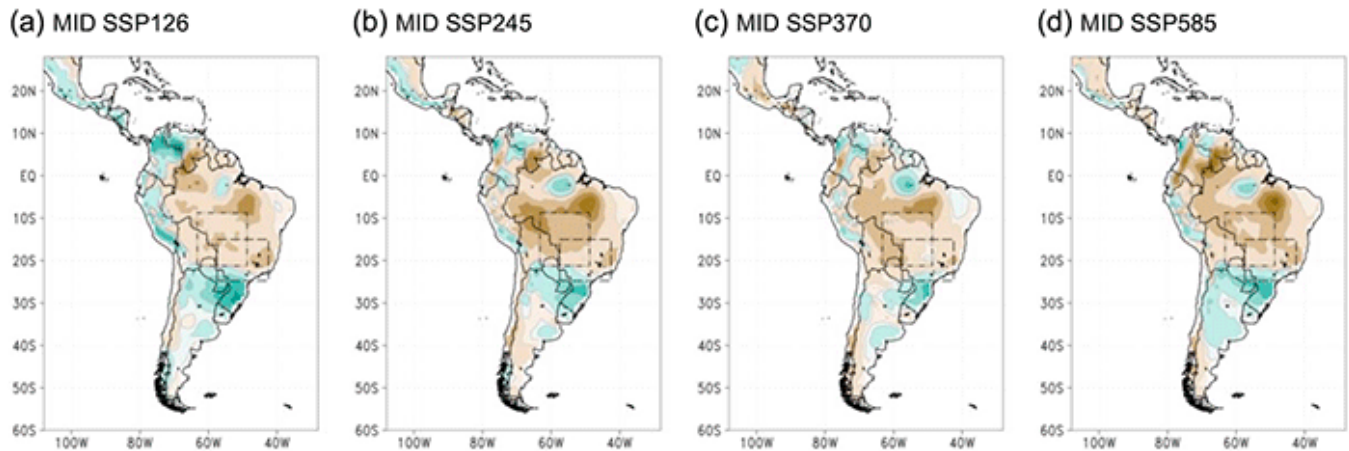


Figure 8. Same as in Figure 7, except for MPI-ESM1 interpolated into the GFDL-ESM4 mesh.

MRI-ESM2

MID-CENTURY w.r.t. PRESENT: September to November



LATE-CENTURY w.r.t. PRESENT: September to November

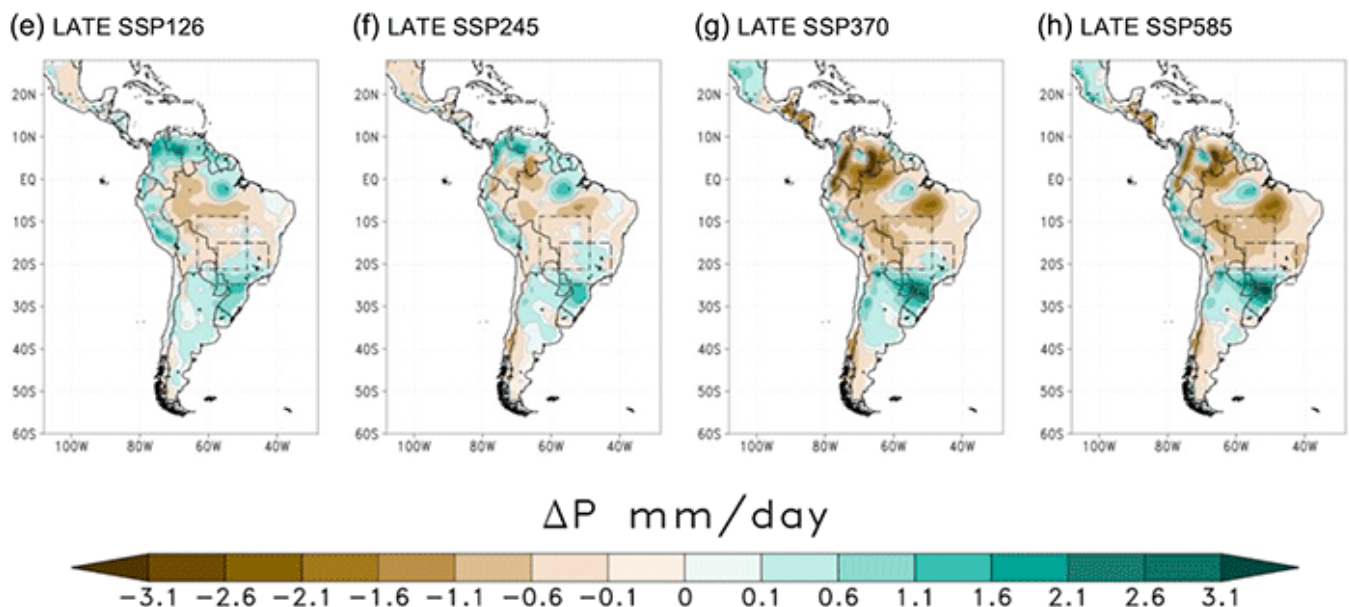


Figure 9. Same as in Figure 7, except for MRI-ESM2 interpolated into the GFDL-ESM4 mesh.

The GFDL-ESM4 model projects a widespread reduction in precipitation by the end of the 21st century. Focusing on the four biomes, GFDL-ESM4 displays enhanced dryness in the late-century period under the SSP370 (Figure 7g) and SSP585 (Figure 7h) scenarios. These dry patterns expand diagonally from the Amazon Basin southeastward, suggesting a connection to the SACZ (Figure 7h). While drier conditions appear to affect all four biomes in the SSP370 and SSP585 projections, they are especially pronounced over the Amazon rainforest, Pantanal, and Cerrado.

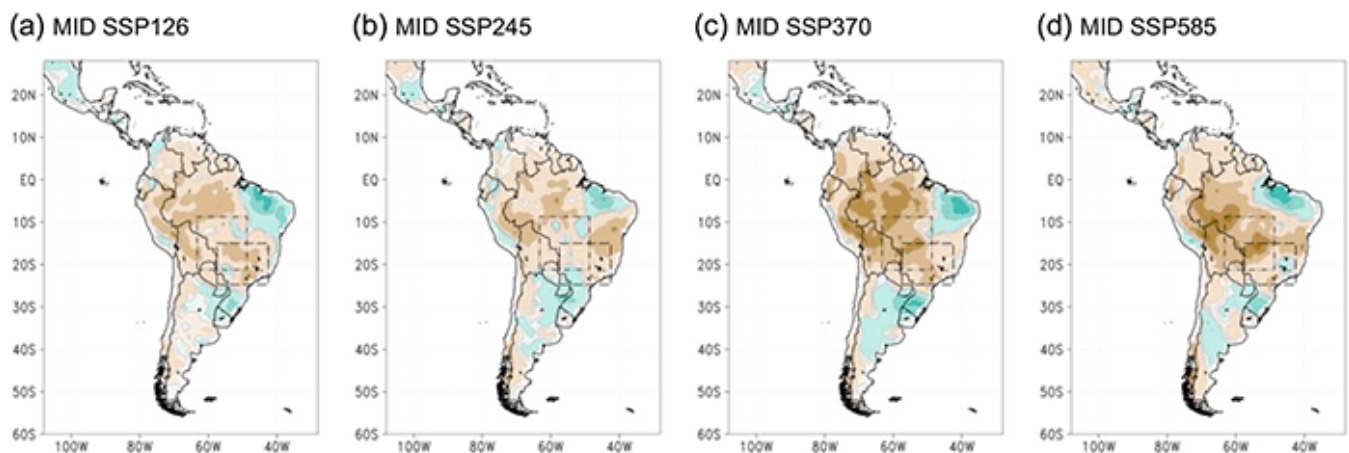
The MPI-ESM1 model appears to corroborate with the dryness projected by GFDL-ESM4, except that it projects wetter conditions over Southern Brazil and Paraguay (encompassing the southern portion of SAMS-2) by the mid and late century (Figure 8). The MRI-ESM2 model (Figure 9) projects a decrease in precipitation in the SAMS, especially in SAMS-1. Conversely, it shows an

increase in precipitation in northern Brazil around the equator, between 55°W and 60°W. Interestingly, it also projects an increase in precipitation in southern Brazil toward the end of the 21st century, with higher rates under SSP370 and SSP585 (Figure 9g, h). Notably, the increase in precipitation over southern Brazil and La Plata Basin, despite some regional differences, appears as a consistent projection across all models during the pre-monsoon season.

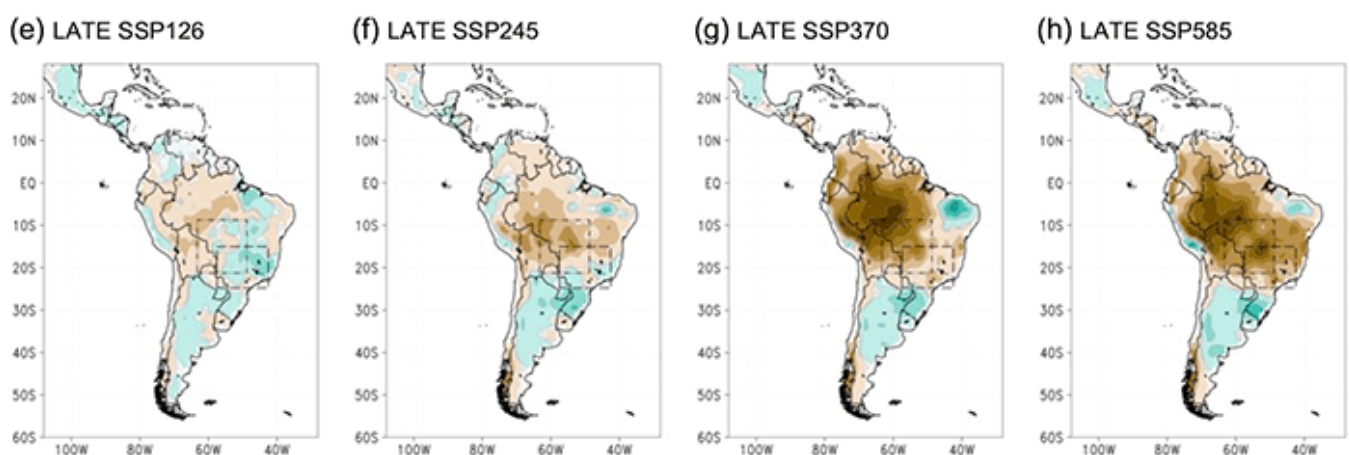
Interestingly, although all models investigated in this article generally agree on the projected changes over tropical and subtropical South America during the pre-monsoon season, the projected changes are less consistent when considering the entire SAMS wet season (October to March) in some models (Figures 10–12). These discrepancies suggest that enhanced precipitation in the peak of the monsoon may offset the suppressed convection during the pre-monsoon in some models.

GFDL-ESM4

MID-CENTURY w.r.t. PRESENT: October to March



LATE-CENTURY w.r.t. PRESENT: October to March



ΔP mm/day

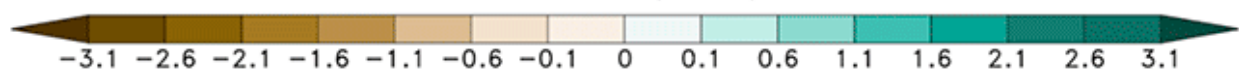


Figure 10. Projected changes in precipitation (ΔP , mm/day) for the entire monsoon period (October–March) in the midcentury (a–d) and late-century (e–h) periods with respect to the present climate. The CMIP6 SSPs—SSP126 (a, e), SSP245 (b, f), SSP370 (c, g), and SSP585 (d, h)—drove the GFDL-ESM4 future climate. Dot-dashed and dashed boxes delimit SAMS-1 and SAMS-2 respectively in all panels.

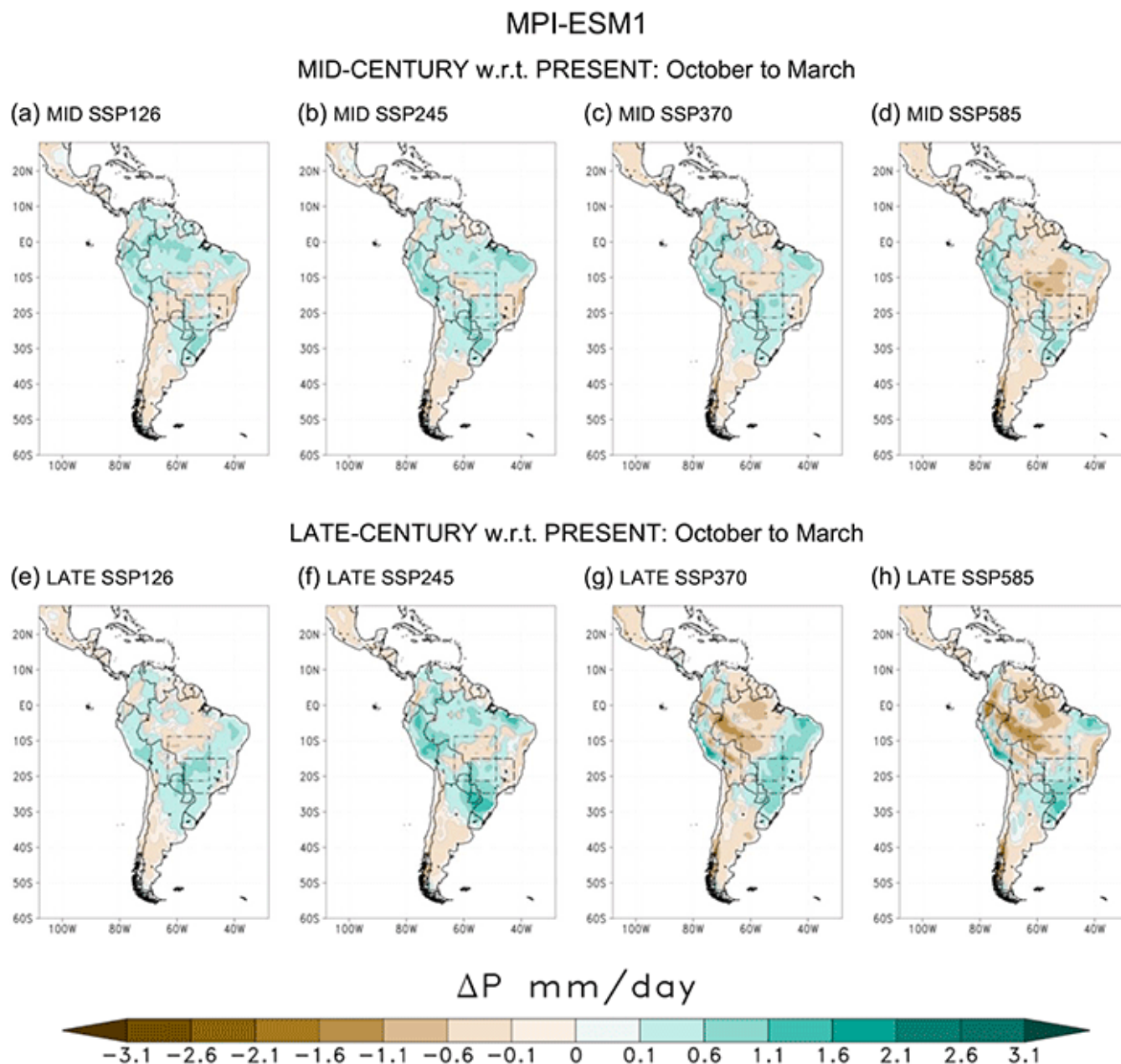


Figure 11. Same as in Figure 10, except for MPI-ESM1 interpolated into the GFDL-ESM4 mesh.

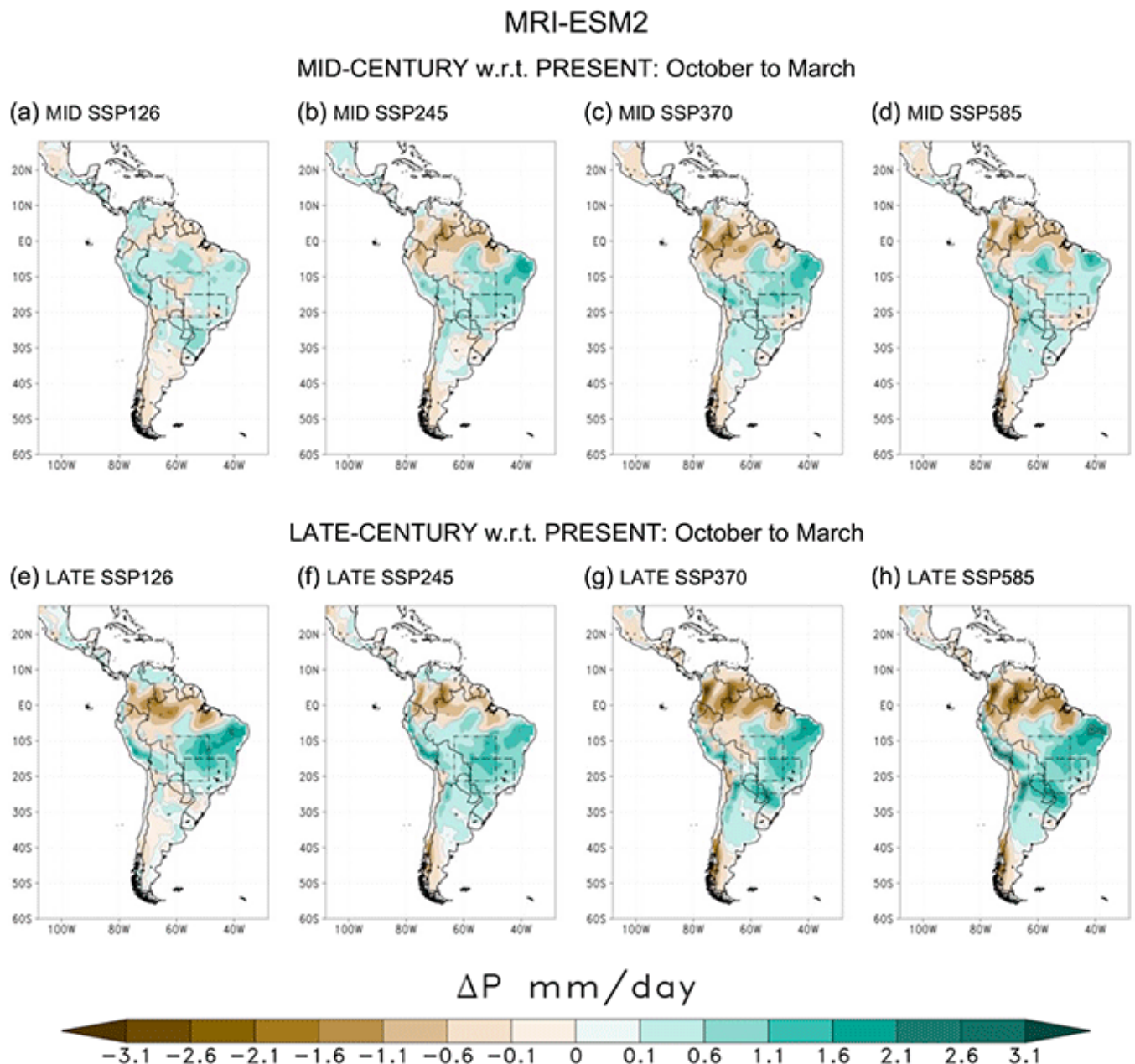


Figure 12. Same as in Figure 10, except for MRI-ESM2 interpolated into the GFDL-ESM4 mesh.

For example, while GFDL-ESM4 generally displays a similar pattern under the most extreme SSP scenario during the pre-monsoon (Figure 7g–h) and the entire wet season (Figure 10g–h), the agreement is not homogeneous across the SAMS domains, especially in the green and intermediate scenarios, SSP126 and SSP245 respectively (Figures 10e, f). Moreover, MPI-ESM1 projects a decrease in precipitation in SAMS-1 and an increase in most of SAMS-2 and southern Brazil (Figure 11). Although MRI-ESM2 displays a reduction in precipitation in the northernmost part of South America, it mostly shows an increase in precipitation toward the end of the century in both the SAMS regions (Figure 12e–h).

Ultimately, the ESMs point to a decrease in precipitation in northwestern South America and an increase in southern Brazil, especially in the late-century period for those neighboring regions of the SAMS. In the SAMS regions, they project a decrease in precipitation in pre-monsoon months (September–November), notably under extreme scenarios; models disagree on the projected precipitation changes when considering the entire rainy season.

Almazroui et al. (2021) assessed precipitation changes in South America using 38 CMIP6 GCMs. Their study addressed near-surface air temperature and precipitation changes in the CRRs in SA using the same SSPs discussed in this article. Some of their findings share similarities with the results presented in this article and agree with the earlier CMIP projections over the SAMS region and surroundings. For example, they concluded that the model ensemble projected a decrease in precipitation over tropical South America and Amazonia and an increase over southeastern South America. Their results indicated that these trends maintain their signal and intensify from the weakest (SSP126) to the strongest (SSP585) scenario and toward the end of the 21st century. They also suggested an enhancement in the rainfall seasonality, with greater contribution from the wetter months to the annual total. Additionally, Reboita et al. (2023) examined precipitation variability and seasonal cycle in five distinct domains over tropical South America using eight CMIP6 GCMs and two scenarios (SSP-4.5 and SSP-8.5). Their trend analyses showed a delay in the onset of the wet season in practically all regions analyzed under these two scenarios by the end of the century.

While similar conclusions have been previously obtained using the set of models and scenarios examined in this article, these results highlight the importance of separating the SAMS from the SACZ. Precipitation regimes and their mechanisms, as simulated in models and observed in nature, can be very distinct in these regions. Discrepancies may arise particularly where the SACZ is more active (SAMS-2), given the importance of tropical–extratropical interactions and teleconnections with coupled modes on intraseasonal-to-interannual timescales. These interactions, though beyond the scope of this article, deserve proper analysis in future assessment of climate change in South America.

Conclusions

The regularity of the SAMS monsoonal regime is vital to millions of people in South America. According to the International Water Management Institute (IWMI), a nonprofit international water management research organization, rainfed agriculture accounts for approximately 90% of the farmed land in the continent. Hydropower is a significant energy source in South America, contributing to approximately 34% of the total electricity supply (Naranjo-Silva et al., 2023). Additionally, the SAMS impacts ecosystems and biodiversity. Shifts in the monsoon can alter the availability of water resources and cause significant influences on food production and infrastructure. These changes can impact the economy and social stability in many countries, alter habitats, and affect flora and fauna. The primary objective of “The SAMS Climatic Features” is to review the main spatiotemporal characteristics and the seasonal cycle of the SAMS, while “The

Anthropogenic Climate Change Impacts on the SAMS Cycle” specifically evaluates how the seasonal cycle of the SAMS may change as the planet warms and the sensitivity of these results to the choice of the global climate model (GCM) and domain.

Like other monsoon systems, the SAMS is driven by differential heating between land and ocean. During summer, land heats up more rapidly than the adjacent ocean, creating a low-pressure system over the landmass. In the case of the SAMS, the low-pressure system is manifested as an anomaly in circulation and pressure over southeastern Brazil. As warm, moist air rises from the ocean to replace the rising air over the land, it carries with it moist static energy. Monsoons tend to coincide with maxima in near-surface MSE. When moist air from the ocean reaches the land, it releases latent heat as it condenses, contributing to the available energy for convection. These processes are also essential in the SAMS.

Moreover, the SAMS is a land–atmosphere convectively coupled system (Gentine et al., 2019). The Amazon rainforest contributes with the buildup of MSE via evapotranspiration. This coupling between the rainforest and the SAMS has been maintained for millions of years, but could be reaching a critical turning point as global warming and aggressive deforestation alter the hydrological cycle in the Amazon (Bochow & Boers, 2023).

Although the SACZ is the most important feature of the SAMS, mechanisms driving convection in the ocean–and–coast and within the continent can be distinct. For instance, the oceanic–SACZ manifests as an interaction between physical and dynamical coupled processes occurring over tropical South America and in midlatitudes of both hemispheres. Convective activity over the continent is affected by local moisture sources and the transport of moisture via low-level jets and cross-equatorial moisture fluxes. These jets appear modulated by midlatitude Rossby wave trains on the Southern Hemisphere and the North Atlantic subtropical high-pressure system on the Northern Hemisphere. Ultimately, these dynamical processes synchronize, and convection is enhanced over the continent and across the western South Atlantic Ocean.

The rapid warming of the oceans and the atmosphere in the 21st century and the respective feedback have numerous repercussions to the hydrological cycle in South America. The greatest challenge in understanding these impacts and separating them from “natural variability” is the lack of reliable records spanning several decades at adequate spatiotemporal resolutions. This is particularly problematic at the core of the SAMS, as demonstrated in this article.

While paleoclimatic records offer promising insights into past climates, their sparseness and limited scope can fall short in providing the necessary information to understand complex mechanisms and interactions affecting the SAMS on low-frequency timescales. Consequently, climatic studies over tropical South America must rely heavily on the ability of reanalyses and GCMs to reproduce the observed climate of the region. Therefore, it is imperative to ensure that existing station datasets continue to be maintained in the future, despite the advancement of satellite technologies and machine learning methods.

Using available precipitation datasets and three CMIP6 global models, the authors demonstrate that GCMs have biases and often exhibit conflicting seasonal cycles over the core of the SAMS and the SACZ. These biases refer to both the total seasonal precipitation and the onset of the wet season.

Furthermore, the findings highlight the sensitivity of the results to the choice of the spatial domain. Consequently, it becomes crucial to meticulously identify and distinguish precipitation regimes in climate reports, aiming to minimize inconsistencies and provide reliable information for stakeholders and policymakers.

Changes in the seasonal cycle and monthly precipitation projected by all models examined in this article indicated great sensitivity to the Shared Socioeconomic Pathways. An investigation of climate projections demonstrated large intermodel spread in precipitation patterns between the present and the mid and late century, independently of the scenario. For example, MRI-ESM2 projected a wetter SAMS in all scenarios by the end of the 21st century, in contrast with GFDL-ESM4, which indicates a much drier SAMS and SACZ in the same period. The most consistent result across models appears to be the enhancement of dry conditions over northwest Amazon and wetter conditions in subtropical South America. Models exhibit great agreement in projections of dry conditions early in the monsoon season, indicating that the anthropogenic climate change may delay the onset of the monsoon. This delay has significant impact to ecosystems that are adapted to the start of the wet season in the Southern Hemisphere spring (between September and October). This delay will impact many species and farmers who count on the onset of the monsoon for their crops.

Nonetheless, when considering the entire wet season, the spatial boundary between “dry tropics–wet subtropics” projections varies across models. Some models (e.g., MPI-ESM1) suggest drier conditions in the SACZ, which can be interpreted as a persistent trend in the poleward shift of the convergence zone (Zilli et al., 2019). Conversely, other simulations (e.g., MRI-ESM2) indicate a significant wetting of southeastern South America or a reversal trend of what has been observed in the first decades of the 21st century.

These results highlight significant deficiencies and model biases in simulating the continental- and oceanic-SACZ. As discussed in this article, the SACZ results from coupled tropical–extratropical interactions. The SACZ’s organization and persistence depend on the transport of moisture and heat from the continent to the ocean, which is enhanced by the propagation of midlatitude wave trains. The trajectory and development of these wave trains are influenced by sea–surface temperature patterns and the position and intensity of the subtropical upper-level jet stream. Realistically reproducing extratropical disturbances (like those associated with midlatitude wave trains) and teleconnections (interactions between distant regions) is essential.

In summary, improving model simulations of the SACZ involves addressing deficiencies related to both tropical–extratropical dynamics and land–ocean interactions. Research should be continually fostered to refine climate models to better capture these complex processes and enhance the understanding of regional climate variability in South America.

While successive generations of Coupled Model Intercomparison Project models have significantly improved upon predecessors, continuous efforts are necessary to properly reproduce the climatic features in the Southern Hemisphere and ultimately increase the confidence in the projected changes.

Nevertheless, there is an unequivocal consensus that tropical South America climate is undergoing significant change over time. Both observations and climate models suggest that the recent drought events affecting the Amazon and Pantanal regions (Marengo et al., 2021) could intensify and become a new norm by the middle and end of the 21st century. Deforestation likely plays a critical role in the anthropogenic alteration of the continent's hydroclimate, leading to unprecedented consequences. Urgent action is imperative to mitigate these impacts; waiting for GCMs to achieve perfect simulations of Earth's climate is not a viable strategy.

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