



**FEDERAL UNIVERSITY OF ITAJUBÁ  
POSTGRADUATE PROGRAM IN ENVIRONMENT  
AND WATER RESOURCES**

**CLIMATE INTERVENTION: EFFECTS OF  
STRATOSPHERIC AEROSOL INJECTION  
ON SOUTHERN HEMISPHERE  
EXTRATROPICAL CYCLONES**

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**PhD THESIS**

**João Gabriel Martins Ribeiro**

**Itajubá–MG, Brazil  
2026**

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STRATOSPHERIC AEROSOL INJECTION  
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by

**João Gabriel Martins Ribeiro**

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Environment and Water Resources/Climate and Sustainability

**Advisor:** Michelle Simões Reboita, PhD

**Itajubá–MG, Brazil  
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**FEDERAL UNIVERSITY OF ITAJUBÁ  
INSTITUTE OF NATURAL RESOURCES  
DOCTORAL PROGRAM IN ENVIRONMENT AND WATER  
RESOURCES**

**JOÃO GABRIEL MARTINS RIBEIRO**

**CLIMATE INTERVENTION: EFFECTS OF  
STRATOSPHERIC AEROSOL INJECTION  
ON SOUTHERN HEMISPHERE  
EXTRATROPICAL CYCLONES**

Thesis approved by the examining committee on  
March 26, 2026, granting the author the title of  
Doctor of Science in Environment and Water  
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*To my daughter, Arya, the reason for my hope in the future;  
to my wife Alana, my tireless companion at all times; and to  
every person who contributed with teachings and  
experiences that enriched this journey, I dedicate this  
achievement.*

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“With my lightnin' bolts a-glowin  
I can see where I am goin' to be  
When the reaper he reaches and touches my hand”

**Arcade Fire - Wake Up**

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## ABSTRACT

RIBEIRO, João Gabriel Martins. **Climate Intervention: Effects of Stratospheric Aerosol Injection on Southern Hemisphere Extratropical Cyclones**. 2026, 132 p. Thesis (Doctorate in Environment and Water Resources) - Natural Resources Institute, Federal University of Itajubá, Itajubá, 2026.

Since the long residence time of greenhouse gases in the atmosphere limits the immediate effectiveness of traditional mitigation techniques, Climate Intervention (CI) approaches, specifically Stratospheric Aerosol Injection (SAI), emerge as potential strategies to reduce global warming. However, the impacts of SAI on components of the climate system, particularly on extratropical cyclones (ETCs) in the Southern Hemisphere, remain poorly understood, despite the high vulnerability of coastal regions to these systems. This study aimed to fill this gap by assessing the impacts of SAI on ETCs climatology, and their associated precipitation and winds, focusing on subdomains of South America, Southern Africa, and Australia. To this end, climate projections from the GeoMIP, GLENS, and ARISE-SAI international modeling projects were used, comparing scenarios with and without the application of SAI. The results indicate that, although the frequency of cyclones shows a decreasing trend in both future scenarios, the reduction is statistically less pronounced under SAI scenarios. Crucially, while unrestricted global warming (without SAI) projects an intensification of cyclones (lower central pressures), the implementation of SAI reduces this effect, keeping the intensity of the systems closer to that of the present climate. Regarding the associated impacts, it was observed that SAI induces a general weakening in precipitation and wind intensity at 10 meters generated by cyclones compared to scenarios without intervention. Consequently, the percentage contribution of cyclones to annual precipitation and wind totals tends to decrease from the near to the distant future under the influence of SAI, suggesting that this technique acts by bringing the dynamic and thermodynamic characteristics of cyclones closer to historical reference conditions. These findings highlight the problem that, although SAI is effective in mitigating the intensity of cyclones, it does not restore the climate to a state similar to the reference period, requiring assessments of potential risks and side effects. Thus, the implementation of intervention strategies requires caution and robust scientific research. Future studies need to improve high-resolution modeling and possible alternative strategies, as well as integrated research on other tipping points. Above all, there is an urgent need to include the Global South contexts in the risk assessments and governance of these technologies.

**Keywords:** climate intervention; stratospheric aerosol injection; extratropical cyclones; climate change.

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## RESUMO

RIBEIRO, João Gabriel Martins. **Intervenção Climática: Efeitos da Injeção de Aerossóis Estratosféricos nos Ciclones Extratropicais do Hemisfério Sul**. 2026, 132 p. Tese (Doutorado em Meio Ambiente e Recursos Hídricos) - Instituto de Recursos Naturais, Universidade Federal de Itajubá, Itajubá, 2026.

Uma vez que o longo tempo de residência dos gases de efeito estufa na atmosfera limita a eficácia imediata das técnicas de mitigação tradicional, as técnicas de Intervenção Climática (IC), especificamente a Injeção de Aerossóis Estratosféricos (do inglês, *Stratospheric Aerosol Injection* - SAI), emergem como estratégias potenciais para reduzir o aquecimento global. Contudo, os impactos da SAI sobre os componentes do sistema climático, em particular nos ciclones extratropicais (CEs) do Hemisfério Sul, permanecem pouco compreendidos, apesar da alta vulnerabilidade das regiões costeiras a estes sistemas. Este estudo visou preencher essa lacuna avaliando os impactos da SAI na climatologia dos CEs, bem como na precipitação e ventos associados a esses sistemas, com foco nos subdomínios da América do Sul, África Austral e Austrália. Para tal, foram utilizadas projeções climáticas dos projetos internacionais de modelagem GeoMIP, GLENS e ARISE-SAI, comparando cenários com e sem a aplicação de SAI. Os resultados indicam que, embora a frequência de ciclones apresente tendência de queda em ambos os cenários futuros, a redução é estatisticamente menos acentuada sob cenários de SAI. Crucialmente, enquanto o aquecimento global irrestrito (sem SAI) projeta uma intensificação dos ciclones (menores pressões centrais), a implementação da SAI reduz esse efeito, mantendo a intensidade dos sistemas mais próxima à do clima presente. Em relação aos impactos associados, observou-se que a SAI induz um enfraquecimento geral na precipitação e na intensidade do vento a 10 metros gerados pelos ciclones em comparação aos cenários sem intervenção. Consequentemente, a contribuição percentual dos ciclones para os totais anuais de precipitação e vento tende a diminuir do futuro próximo para o distante sob a influência da SAI, sugerindo que esta técnica atua aproximando as características dinâmicas e termodinâmicas dos ciclones das condições do período de referência. Estes achados evidenciam a problemática de que a SAI, embora eficaz na contenção da intensidade dos ciclones, não restaura o clima a um estado análogo ao passado, sendo necessárias avaliações de riscos potenciais e de efeitos colaterais. Assim, a implementação de estratégias de intervenção exige cautela e um aprofundamento científico robusto. Em estudos futuros é necessário o aprimoramento de modelagem de alta resolução e possíveis estratégias alternativas, bem como a investigação integrada de outros pontos de não retorno (*tipping points*). Sobretudo, destaca-se a urgência de inserir o contexto do Sul Global nas avaliações de risco e governança destas tecnologias.

**Palavras-Chave:** intervenção climática; injeção de aerossóis estratosféricos; ciclones extratropicais; mudanças climáticas.

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## LIST OF ABBREVIATIONS AND ACRONYMS

AFR	–	Southern Africa
ARISE-SAI	–	Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol injection
AUS	–	Australia
BECCS	–	Bioenergy with Carbon Capture and Storage
CCT	–	Cirrus Cloud Thinning
CDR	–	Carbon Dioxide Removal
CESM	–	Community Earth System Model
CH <sub>4</sub>	–	Methane
CI	–	Climate Intervention
CMIP	–	Coupled Model Intercomparison Project
CMIP6	–	Phase Six of CMIP project
CO <sub>2</sub>	–	Carbon Dioxide
DACCS	–	Direct Air Capture
ETCs		Extratropical Cyclones
GCMs	–	Global Climate Models
GeoMIP	–	Geoengineering Model Intercomparison Project
GeoMIP6	–	Six phase of GeoMIP
GHGs	–	Greenhouse Gases
GLENS	–	Stratospheric Aerosol Geoengineering Large Ensemble
IPCC	–	Intergovernmental Panel on Climate Change
MCB	–	Marine Cloud Brightening

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MPI	–	Max Planck Institute
N <sub>2</sub> O	–	Nitrous Oxide
RCP8.5	–	Representative Concentration Pathway 8.5
SAI	–	Stratospheric Aerosol Injection
SAO	–	Southwestern Atlantic Ocean
SSP2-4.5	–	Shared Socioeconomic Pathways 2-4.5
SO <sub>2</sub>	–	Sulfur Dioxide
SRM	–	Solar Radiation Management
UNFCCC	–	United Nations Framework Convention on Climate Change
WACCM	–	Atmosphere Community Climate Model

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## 1. INTRODUCTION

The Earth's climate system is fundamentally sensitive and shaped by the composition of its atmosphere. For millennia, despite natural variations, concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) remained within a comparable range ([Logan et al., 1981](#); [Ramanathan et al., 1987](#); [Hauglustaine et al., 1994](#); [Möller, 2014](#)). This balance began to break down with the onset of the Industrial Revolution in the late 18th century. The large-scale burning of fossil fuels, deforestation, and intensive land-use changes, initiated an unprecedented release of anthropogenic GHGs into the atmosphere ([Hauglustaine et al., 1994](#); [Isaksen et al., 2009](#); [Pongratz and Caldeira, 2012](#); [Minx et al., 2021](#); [IPCC, 2023](#)). These emissions led to concentrations never before seen and outside the natural variability. Such changes were so profound that they popularized the concept of the Anthropocene (a term of social and environmental significance rather than a formal geological epoch) to describe the era in which human activity became the dominant influence on the climate and the environment ([Crutzen, 2002](#); [Marshman et al., 2019](#)).

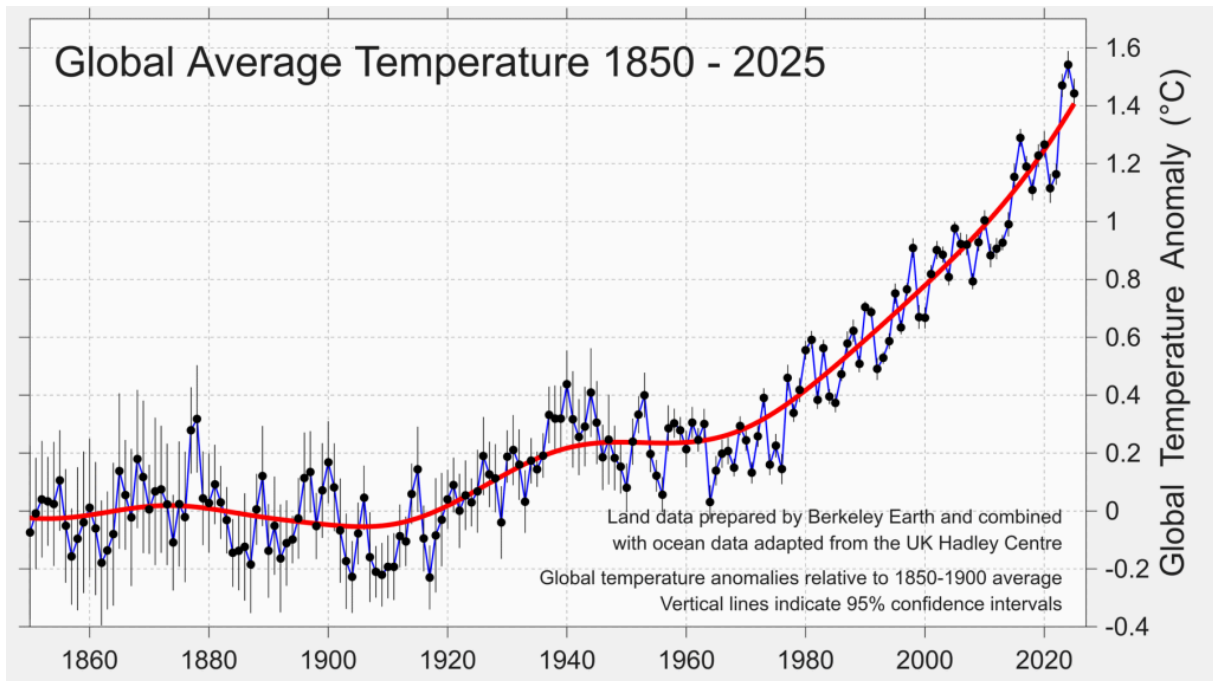
Although the natural greenhouse effect is essential for life on planet Earth, these anthropogenic emissions have profoundly altered the radiative balance and disrupted the Earth's radiative equilibrium. Greenhouse gases trap some of the longwave radiation leaving the Earth, amplifying the natural greenhouse effect and leading to positive radiative forcing and net energy accumulation in the climate system ([Hansen et al., 2007](#); [Wigley, 2021](#); [Fuglestedt et al., 2023](#); [Filonchyk et al., 2024](#); [Irfan et al., 2024](#)). The main consequence is global warming, but the impacts spread throughout the planetary system, disrupting established patterns and increasing the frequency and intensity of extreme weather events ([Hansen et al., 2010](#); [Clarke et al., 2022](#); [Reboita and Ambrizzi, 2022](#)). In addition, this change impacts the climate system, reaching tipping points (irreversible changes in the climate system) which, once exceeded, can cause disruptions in known patterns ([Lenton et al., 2007](#); [Abrams et al., 2023](#)).

Studying these tipping points is of paramount importance because they represent critical thresholds where relatively small additional increments in global temperature can trigger non-linear, self-reinforcing, and often cascading effects across the globe ([Lenton et al., 2019](#); [McKay et al., 2022](#)). The implications for the Earth's climate system are profound; crossing these boundaries could lead to the irreversible collapse of the Greenland and West Antarctic ice sheets, the dieback of the Amazon rainforest, or abrupt shifts in global ocean circulation patterns, such as the Atlantic Meridional Overturning Circulation (AMOC) ([Dakos et al., 2024](#); [Boulton et al., 2022](#); [Westen et al., 2024](#)). Currently, the GHGs emission trajectory is pushing the planet dangerously close to several of these thresholds. Recent scientific assessments warn that even if warming is limited to the Paris Agreement target of 1.5 °C to 2.0 °C, the risk of triggering multiple climate tipping points remains uncomfortably high, underscoring the urgency for both rapid mitigation strategies and a deeper understanding of alternative climate interventions ([McKay et al., 2022](#); [IPCC, 2023](#)).

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The increase in global average surface temperature provides the most unequivocal evidence of the changes in the climate (**Figure 1**, data from combined product from land stations land stations and models - available at: <https://berkeleyearth.org/>, IPCC, 2023). Although the climate has undergone natural variations over the centuries, since the post-industrial period there has been a marked and accelerating trend toward warming. According to recent records, 2024 was the first year to reach the 1.5 °C mark ([The Copernicus Programme, 2024](#); [Bevacqua et al., 2025](#)) compared to pre-industrial records. This warming is not spatially uniform; land areas warm faster than oceans, and polar regions experience amplification that triggers feedback loops, such as reduced ice albedo ([Forster et al., 2025](#)).



**Figure 1** - Global surface temperature anomaly (°C) between 1850 and 2025 relative to average values between 1850 and 1900. Monthly (blue line) means with the respective monthly standard deviation (vertical black line) and annual (red line) average values are shown. Source: Adapted from [Berkeley Earth \(2026\)](#).

Global Climate Models (GCMs) are used to understand how this warming occurred and how it is evolving. Developments within the Coupled Model Intercomparison Project (CMIP), particularly phase six of this project (CMIP6 cycle), have demonstrated greater ability to reproduce historical climate patterns and variability, providing greater confidence in recent (2015-2025) and long-term projections ([Eyring et al., 2016](#); [Carvalho et al., 2022](#); [Forster et al., 2025](#)). In general, GCMs consistently project further temperature increases throughout the 21st century, depending on emission scenarios ([Ajjur and Al-Ghamdi, 2021](#); [Almazroui et al., 2021](#)); i.e. suppositions about human development. These scenarios provide narrative descriptions of how global society may evolve in terms of population, economic growth, and technological development. These narratives are translated into quantitative



trajectories of GHGs concentrations and radiative forcing, serving as crucial inputs for models that estimate future climate change.

The world has already temporarily exceeded the 1.5 °C limit set by the Paris Agreement, a limit that aims to avoid the most catastrophic impacts ([UNFCCC, 2015](#); [IPCC, 2018](#); [McKay et al., 2022](#)) reaching the tipping points. Projections indicate that warming could exceed 2 °C, signaling that the window for conventional mitigation to avoid drastic interference in the climate system is rapidly closing ([Hueholt et al., 2024](#); [Lockie et al., 2024](#)).

The consequences of this temperature increase are already being felt globally, but they pose a disproportionate ([IPCC, 2014](#); [Althor et al., 2016](#); [Otto et al., 2020](#)) threat to the Global South (a geopolitical concept used to refer to developing, emerging, or peripheral economies). Developing countries are disproportionately vulnerable due to their geographical exposure, limited adaptive capacity, economic dependence on climate-sensitive sectors ([Nagy et al., 2018](#)). These impacts include the intensification of extreme weather events, such as heat waves, prolonged droughts, and extreme precipitation. Thus, these threats pose dangers in the countries of Global South, exacerbating poverty, food insecurity, and inequality ([Lahsen and Ribot, 2021](#); [Otto, 2023](#)).

An aggravating factor in the context of climate change and its mitigation is the issue of the long lifetime of CO<sub>2</sub> and the other GHGs in the atmosphere. Even if global emissions were to stop today (a scenario far from current reality), the existing stock of greenhouse gases would continue to warm the planet for centuries ([Ehlert and Zickfeld, 2017](#); [Goodwin et al., 2014](#); [Dvorak et al., 2022](#)). The concept of “net-zero” emissions, a state in which any remaining emissions are balanced by removals from the atmosphere, is the stated goal of the Paris Agreement. However, the current trajectory of emissions and the slow pace of decarbonization put the world far from achieving this goal in time to avoid dangerous warming ([Bataille et al., 2020](#); [Buck et al., 2023](#); [Battersby, 2024](#)). This problem implies that mitigation alone, while crucial, may no longer be sufficient to avoid impacts on the climate system

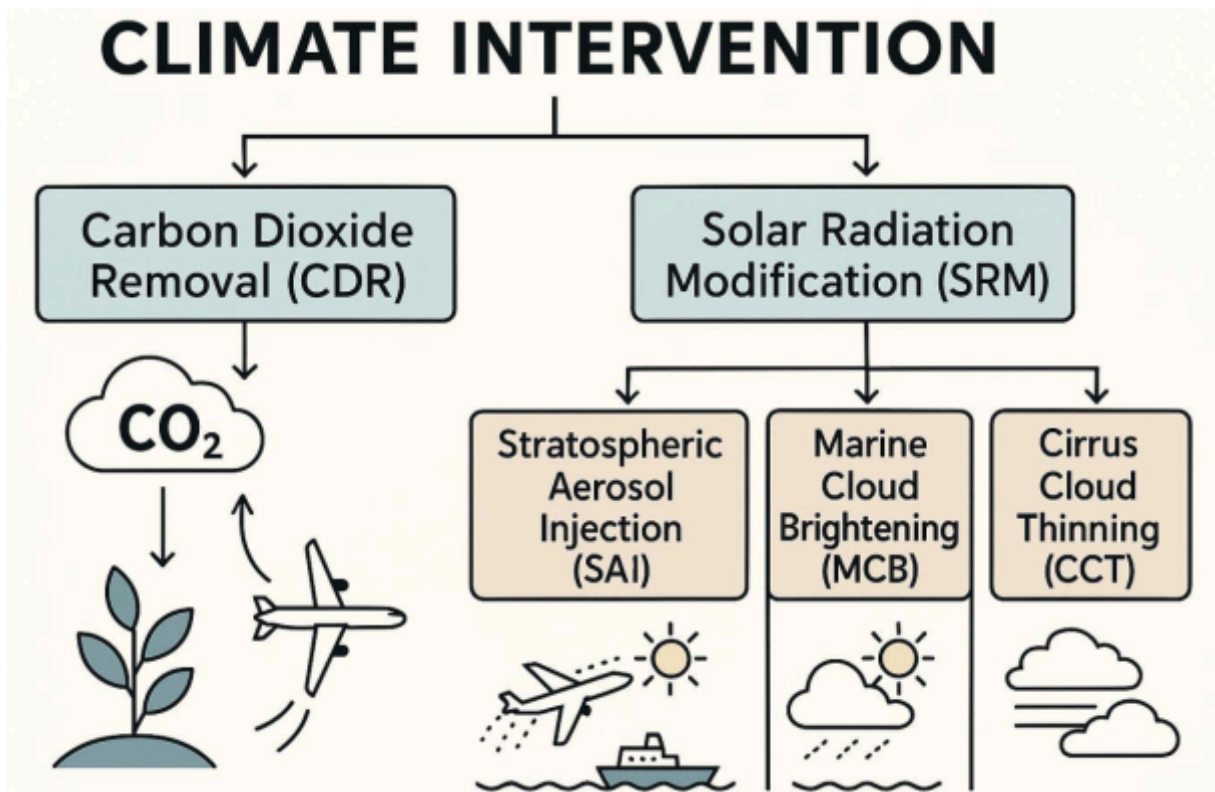
## 1.1 Climate Intervention

Faced with all these problems, Climate Intervention (CI) techniques (**Figure 2**), also known as geoengineering, have emerged as a potential complementary strategy to limit global warming ([Shepherd, 2009](#); [Robock, 2020](#)). These techniques, although controversial, show promise in helping to address climate change in a context where conventional mitigation measures seem insufficient to deal with the scale and urgency of the crisis ([Lin, 2020](#)). Scientific interest in CI has evolved over the past two decades, moving from theoretical speculation to an active field of research, with a growing body of literature exploring its potential and pitfalls (e.g., [Royal Society, 2009](#); [Möller, 2023](#); [Graham, 2025](#)). It is often argued that humanity is already conducting a massive and uncontrolled geoengineering experiment by releasing gigatons of carbon into the atmosphere; CI research, on the other

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hand, seeks to understand the potential of controlled intervention to reduce risks ([Reynolds, 2019](#); [McLaren, 2025](#), [Simon et al., 2025](#)).

The central premise of CI is to deliberately intervene in the climate system to temporarily neutralize the warming effect of greenhouse gases. The initial experimental idea behind CI refers to the similarities of the cooling effect observed after major volcanic eruptions ([Robock, 2000](#); [Haywood et al., 2013](#); [Robock, 2012](#); [Kravitz et al., 2013](#)). Inspired by this observation, one of the proposed CI methods, called Solar Radiation Management (SRM), particularly Stratospheric Aerosol Injection (SAI), has gained prominence. SAI aims to increase the planet's albedo by injecting reflective aerosols into the stratosphere, thereby reducing the amount of solar energy absorbed by the Earth system ([Kravitz et al., 2012](#); [2013](#)). Other techniques (**Figure 2**) such as Marine Cloud Brightening (MCB, [Latham et al., 2012](#); [Haywood et al. 2023](#); [Hirasawa et al., 2023](#)), Carbon Dioxide Removal (CDR, [Smith et al., 2024](#)), and Cirrus Cloud Thinning (CCT, [Mitchell and Finnegan, 2009](#)) are also under constant evaluation.



**Figure 2** - Illustration summarizing the main climate intervention techniques: Carbon Dioxide Removal (CDR), Solar Radiation Modification (SRM), which includes: Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), and Cirrus Cloud Thinning (CCT). Adapted from [Reboita \(2025\)](#).

The physical principle underlying the SAI strategies is based on the conversion of injected sulfur dioxide ( $\text{SO}_2$ ) gas into the stratosphere to sulfate aerosols. After injection into the lower stratosphere,  $\text{SO}_2$  oxidizes to form sulfuric acid vapor, which subsequently nucleates



and condenses into liquid aerosol droplets ([Mills et al., 2017](#)). These sulfate particles are highly efficient at scattering shortwave solar radiation back into space, effectively increasing the Earth's albedo ([Dickinson, 1996](#)). Consequently, this reduction in the solar flux reaching the troposphere generates a negative net radiative forcing that leads to surface cooling, mimicking the natural global cooling observed after large volcanic eruptions ([Robock, 2000](#)).

Modeling studies using GCMs have robustly demonstrated that CI strategies, particularly SAI ([Vioni et al. 2021](#)) and MCB ([Hirasawa et al., 2023](#)), are capable of reducing the rise in global mean surface temperature (**Figure 3**). By enhancing the planet's albedo, these techniques can induce a cooling effect that partially counteracts the warming driven by anthropogenic greenhouse gas emissions, offering a potential mechanism to stabilize global temperatures within targets that emission reductions alone might miss.

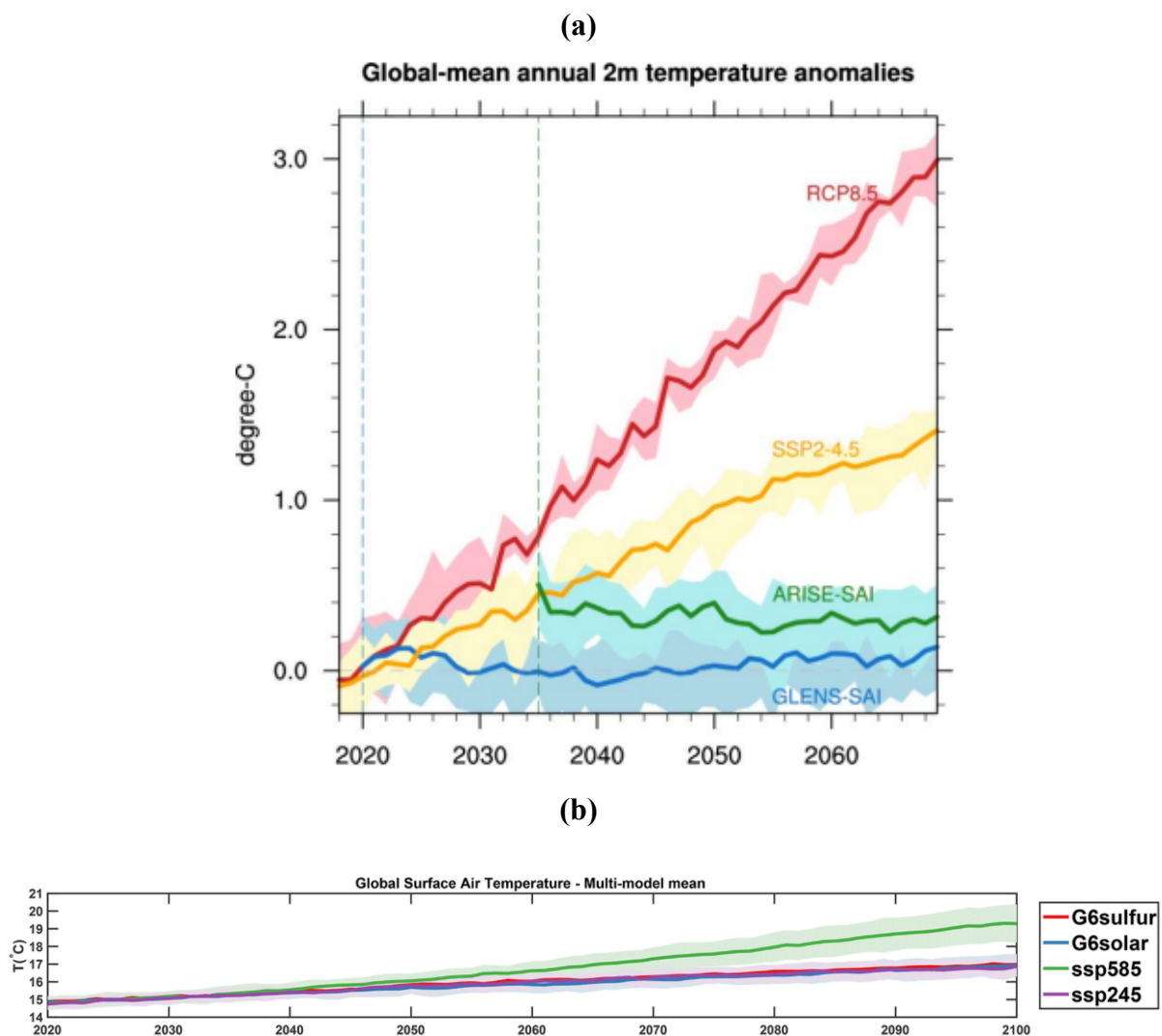
In this approach, projects simulating SAI in GCMs have gained increasing prominence. The first major experiment of this kind was the Stratospheric Aerosol Geoengineering Large ENSEMBLE (GLENS), which provided the first comprehensive dataset for assessing the impacts of large-scale geoengineering. Conducted using the Community Earth System Model (CESM) version 1 with the Whole Atmosphere Community Climate Model (WACCM) version 5 model, GLENS is defined by its goal of maintaining not only the global mean surface temperature but also the interhemispheric and equator-pole temperature gradients at 2020 levels ([Tilmes et al., 2018](#)). To achieve these three simultaneous goals under the high-emission Representative Concentration Pathway 8.5 (RCP8.5) scenario, the project employed a sophisticated feedback control strategy that injects yearly SO<sub>2</sub> at four distinct latitudes (30°N, 15°N, 15°S, and 30°S) into the stratosphere (~5 km above the tropopause), all under an arbitrary longitude chosen at 180° starting in 2020 as described by [Kravitz et al. \(2017\)](#). This approach allowed for a robust assessment of regional climate responses and extreme events, minimizing some of the side effects associated with simpler injection strategies, such as excessive tropical cooling ([Tilmes et al., 2018](#)).

To address some of the limitations presented in GLENS, the project **Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection (ARISE-SAI)** represents a new generation of simulations designed to be more relevant to public policy. Described by [Richter et al. \(2022\)](#), these simulations use the Community Earth System Model (CESM) version 2 with the WACCM version 6, using the same GLENS emission locations but at an altitude of ~21.5 km. Unlike previous experiments, which often used high-emission baselines, ARISE-SAI employs a moderate emission scenario (Shared Socioeconomic Pathways 2-4.5; SSP2-4.5) and introduces SO<sub>2</sub> injection starting in 2035. The specific objective of this deployment strategy is to maintain the global average surface air temperature close to 1.5 °C above pre-industrial levels throughout the 21st century, using a feedback control algorithm to determine the amount of sulfur dioxide injection required annually ([Richter et al., 2022](#)).

Complementing these large sets of unique models, the **Geoengineering Model Intercomparison Project (GeoMIP)** facilitates the comparison of results between different Earth System Models to assess robustness and uncertainty. In its sixth phase (GeoMIP6), the G6Sulfur experiment was proposed to simulate the effects of SAI in the latest CMIP6



scenarios. As detailed by [Visioni et al. \(2021\)](#), the G6Sulfur protocol aims to reduce the radiative forcing of the high-level emissions scenario (Shared Socioeconomic Pathways 5-8.5; SSP5-8.5) to match the levels of the mid-level scenario SSP2-4.5. Alongside it, the G6Solar experiment was introduced as a more theoretical, idealized counterpart. It achieves the same cooling target by simply reducing the solar constant, serving primarily as a baseline to isolate and compare the specific climatic impacts of sulfate aerosols against a generic reduction in solar radiation. However, unlike GLENS and ARISE-SAI, here the injection is uniformly made between 10 °N and 10 °S at an altitude of 18 and 20 km, under a single longitudinal band at 0° with minor variations depending on the model. Participating models achieve this by continuously adjusting the amount of stratospheric sulfate injected (or aerosol optical depth) to match the target radiative forcing, providing crucial insights into how different model physics affect the predicted results of SSRM ([Kravitz et al., 2015](#); [Visioni et al., 2021](#)).



**Figure 3 - (a)** Anomalies in global average surface air temperature (°C) for the period 2015–2024, for CESM1-WACCM RCP8.5 (red), CESM2-WACCM SSP2-4.5 (orange), and for the GLENS (blue) and ARISE-SAI (green) experiments. The shaded areas show the range



of values among the simulation members. The vertical blue and green lines mark the start of SAI in GLENS (2020) and ARISE-SAI (2035) **(b)** Global mean temperature ( $^{\circ}\text{C}$ ), with the multi-model mean at the base and shading indicating the standard deviation ( $1\sigma$ ). The green line indicates projections under SSP5-8.5, the purple line SSP2-4.5, and the blue and red lines indicate the G6solar and G6sulfur experiments, respectively. Adapted from [Tilmes et al. \(2018\)](#), [Richter et al. \(2022\)](#) and [Visioni et al. \(2021\)](#).

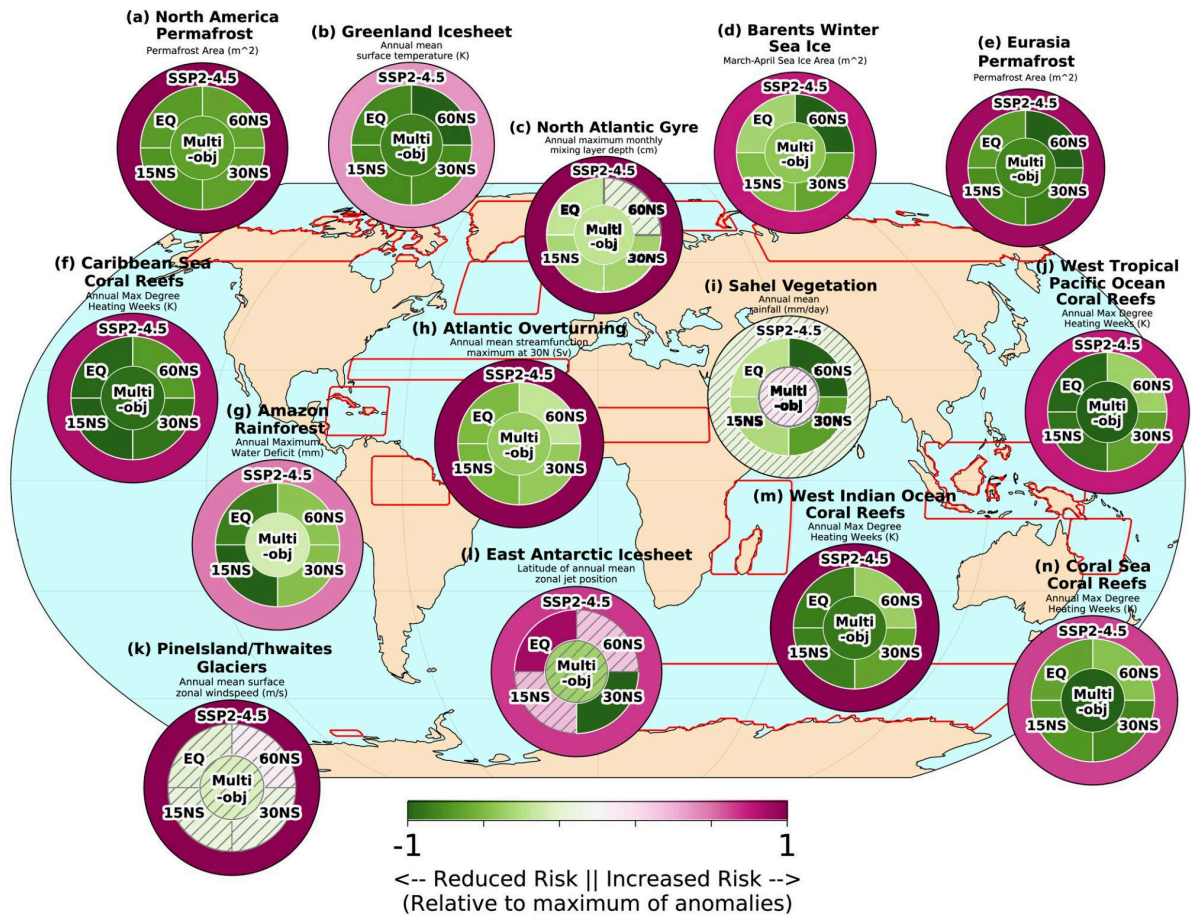
Despite its potential to rapidly reduce global temperatures, SRM is fraught with uncertainties and risks, including possible disruptions to regional precipitation patterns, stratospheric chemistry, and the hydrological cycle ([Harrison et al., 2021](#); [Huynh and McNeill, 2024](#)). In addition, possible regional side effects and complex governance challenges must be assessed ([McGee et al., 2020](#); [Horton et al., 2025](#)). Despite the controversies, the goal of scientific research in this domain is not to advocate for deployment, but to rigorously evaluate its ability to offset warming, the potential impacts, benefits, and side effects of such strategies, providing a solid evidence base for future decision-making.

Beyond the general stabilization of mean temperatures, a critical motivation for investigating SAI is its potential to prevent the Earth system from crossing climate tipping points. Recent research by [Zhao et al. \(2025\)](#) suggests that SAI could play a key roles in keeping the climate system away from these dangerous thresholds, specifically by shaving off peak global warming (peak-shaving), slowing the rate of rapid regional temperature increases (such as Arctic amplification) and reducing the extreme thermal stress that drives ice sheet destabilization and biome diebacks. By effectively reducing maximum temperatures, the deployment of SAI could prevent or significantly delay the triggering of tipping elements that would otherwise be transgressed in high-emission scenarios. However, the efficacy of SAI in preserving these systems is complex and highly dependent on the deployment strategy employed.

As illustrated in **Figure 4**, recent assessments comparing different injection locations (ranging from equatorial to polar strategies) reveal distinct regional outcomes for various tipping elements. The outer ring represents the magnitude of change for specific climate variables (tipping point metrics) in the unmitigated SSP2-4.5 scenario relative to the recent past. The inner sections correspond to the distinct impacts of various SAI strategies (such as equatorial, mid-latitude, or multi-objective approaches) relative to the SSP2-4.5 baseline. Essentially, the colors in the inner sections (greenish colors) that contrast with the outer ring (purple colors) indicate that the SAI strategy is reducing the climate risk trend driven by GHGs, while the hatched areas denote changes that are not statistically significant.

Nevertheless, trade-offs exist: strategies focusing on high-latitude injections tend to be more effective in preserving cryospheric elements, such as the Barents Sea ice and permafrost ([Zhang et al., 2024](#)). Conversely, low-latitude injections demonstrate greater potential for stabilizing tropical tipping elements, such as the Amazon rainforest and coral reefs, highlighting that the optimal strategy depends on the specific climate targets prioritized ([Hirasawa et al., 2023](#); [Zhao et al., 2025](#)).

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**Figure 4** - Response of selected tipping element metrics under SSP2-4.5 and different SAI strategies targeting 1.0 °C stabilization. The outer ring depicts changes under SSP2-4.5 (2050–2069 relative to 2008–2027), while the inner sections illustrate the impact of various SAI strategies (Multi-objective, Equator (EQ), 15N+15S, 30N+30S, and 60N+60S) relative to the SSP2-4.5 baseline. Hatching indicates statistically non-significant changes ( $p > 0.05$ ). Adapted from [Zhao et al., 2025](#).

This research represents one of the pioneering efforts in Brazil to systematically investigate the impacts of CI through the perspective of climate modeling, with a specific focus on the Southern Hemisphere. By investigating the response of extratropical cyclones climatology in the Southern Hemisphere to the SAI, this research aims to provide critical information to the scientific community and policymakers, and help democratize knowledge in this emerging field by making the implications of these technologies transparent for the public.

## 1.2 Object of Study: Extratropical cyclones



Extratropical cyclones (ETCs) are synoptic-scale low-pressure systems characterized by lower pressure at their center than in adjacent regions. They are constantly active and responsible for changes in the weather and climate of the regions where they occur ([Reboita et al., 2023](#)). These systems have a marked diameter, typically ranging from 1,500 to 5,000 km ([Reboita et al., 2010](#)), and rotate clockwise in the Southern Hemisphere. ETCs play a key role in the Earth's general circulation, contributing to the redistribution of heat and moisture between latitudes, transporting warm air masses toward the poles and cold air masses toward the tropics, in a process that seeks to achieve thermal equilibrium in the atmosphere ([Reboita and Marrafon, 2021](#); [Bartolomei et al., 2023](#)).

The formation of ETCs occurs preferentially in the extratropics, at mid to high latitudes, typically in a band around 45 °S ([Reboita et al., 2023](#)). These regions of genesis are marked by zones of intense baroclinicity, i.e., by steep horizontal temperature gradients ([Marrafon et al., 2021](#)). The process of ETC formation (cyclogenesis) can occur through the interaction of these horizontal surface temperature gradients or through the influence of waves in the middle and upper levels of the atmosphere (e.g., between 500 hPa and 200 hPa), or through the coupling of both ([Reboita et al., 2010](#)).

As the main systems responsible for synoptic-scale weather variability in mid-latitudes, ETCs often cause cloudiness, heavy precipitation, and strong winds ([Reboita and Marrafon, 2021](#)). These intense winds, when over the ocean, can result in sea level rise (such as storm surges), coastal erosion, and, in extreme cases, even meteorological tsunamis ([Bartolomei et al., 2023](#)).

In scenarios of climate warming without intervention, general circulation models generally project a shift in storm tracks toward the pole ([Reboita et al., 2021a,b](#)). This trend is confirmed by studies that indicate a decrease in the frequency of cyclones at mid-latitudes and an increase at higher latitudes (around Antarctica). Additionally, multimodel climate projection studies for the Southern Hemisphere indicate that, although the total number of cyclones may decrease in the regions analyzed, the remaining extratropical systems tend to become more intense ([Reboita et al., 2021a,b](#)). Given the importance of these systems and their impacts on vulnerable coastal regions, such as the Global South, investigating how CI, through SAI, can alter the climatology (frequency, intensity, and trajectory) of ETCs is a crucial motivation for this study.

Thus, this work aims to fill a significant knowledge gap and contribute to a more comprehensive understanding of the potential consequences of climate intervention for vulnerable regions in the Global South.

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## 2. MOTIVATION

The motivation for this research is directly linked to the increase in the projected intensity of extratropical cyclones (Southern Hemisphere: [Reboita et al., 2021](#), [Marrafon et al., 2021](#); Northern Hemisphere: [Raible et al., 2020](#); Australia: [Pepler and Dowdy, 2022](#); and Africa: [Chinta et al. 2025](#)) as a consequence of global warming driven by GHGs emissions. These systems are associated with extreme events that cause flooding and wind gusts, which can devastate coastal regions and disrupt economic activities and essential infrastructure, such as maritime and air transport ([Sparks, 2003](#); [Pereira et al., 2021](#)). Given the lack of specific studies on the impacts of CI in the Southern Hemisphere, particularly on the climatology and characteristics associated with extratropical cyclones, this study aims to fill this gap by assessing how the SAI technique can influence the intensity, frequency, trajectory, and extremes of the aforementioned systems. It should be noted that Southern Africa and South America are two regions particularly susceptible to extratropical cyclones and have a low adaptive capacity to climate disasters in the Southern Hemisphere; therefore, special focus is given to them.

The results of this work will have implications not only for the scientific community but also for public policymakers and organizations involved in climate risk mitigation, as increased cyclone intensity can result in significant socioeconomic consequences in these areas. Therefore, understanding the effects of SAI on the modulation of these phenomena is vital for the planning and adaptation of future disaster mitigation strategies.

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### 3. AIMS

#### 3.1. General Aim

The main objective of this study is to determine the impacts of climate intervention by stratospheric aerosol injection (SAI) in future climate projections, specifically focusing on the main characteristics of extratropical cyclones (ETCs) in the Southern Hemisphere. This encompasses both the climatology of these systems and the associated precipitation and winds.

#### 3.2. Specific Aims

The specific objectives of this research are:

- (i) Addressing the existing literature gap (particularly in Brazil), the first specific objective is to analyze the available literature on climate intervention to synthesize its basic concepts and the state-of-the-art discussion on the topic (**Review Article 1**);
  - (ii) To assess the impact of climate intervention on the key characteristics of extratropical cyclones south of 20 °S, including their location, frequency, and lifecycle (**Research Article 2**);
  - (iii) To analyze how climate intervention impacts the associated characteristics of extratropical cyclones, such as: 10-meter wind speed, mean sea level pressure, and precipitation (**Research Article 3**).
-



#### 4. STRUCTURE

The following sections detail the core research articles that constitute this dissertation, aligning the discussion with the overall and specific objectives previously outlined.

**Section 5** discusses **Article 1: "CLIMATE INTERVENTION TECHNIQUES: PROS AND CONS"**, which presents the main issues surrounding climate intervention, including its purposes, techniques, and associated advantages and disadvantages (pros and cons).

**Section 6** is dedicated to **Article 2: "RESPONSE OF THE SOUTHERN HEMISPHERE EXTRATROPICAL CYCLONE CLIMATOLOGY TO CLIMATE INTERVENTION WITH STRATOSPHERIC AEROSOL INJECTION"**, which analyzes how the climatology of extratropical cyclones (ETCs) in the Southern Hemisphere is affected by SAI.

**Section 7** refers to **Article 3**, titled: "**IMPACTS OF STRATOSPHERIC AEROSOL INJECTION ON PRECIPITATION AND WINDS ASSOCIATED WITH EXTRATROPICAL CYCLONES IN THE SOUTHERN HEMISPHERE**". This article complements the analyses presented in Article 2, providing an in-depth examination of the regional and climatic impacts of the SAI on precipitation and 10-m winds associated with Southern Hemisphere ETCs.

Finally, **Section 8** presents the **GENERAL CONCLUSIONS**, integrating the main findings of the entire thesis and discussing the broader implications of climate interventions in the context of global climate change mitigation and research. In addition, suggestions for future studies are presented.

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## 5. CLIMATE INTERVENTION TECHNIQUES: PROS AND CONS

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## Climate Intervention Techniques: Pros and Cons

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## Climate Intervention Techniques: Pros and Cons

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### ABSTRACT

Climate intervention (CI) techniques are strategies proposed to modify the Earth's climate system, aiming to mitigate the adverse effects of climate change. In the current scenario of increasing concern about global warming, these techniques emerge as potential complements to traditional mitigation and adaptation measures. This study aims to review the main CI techniques, such as stratospheric aerosol injection, marine cloud brightening, and carbon dioxide (CO<sub>2</sub>) removal. The adopted methodology includes a comprehensive review of the state of the art and reference works on the topic, evaluating the effectiveness, risks, and challenges associated with each technique. The results show that stratospheric aerosol injection can reduce global temperature by increasing the Earth's albedo, but it may cause adverse effects such as changes in precipitation regimes, depletion of stratospheric ozone, impacts on radiative balance, and ocean acidification. Similarly, marine cloud brightening causes an increase in albedo. On the other hand, CO<sub>2</sub> removal techniques are seen as potential solutions for decarbonization, although they face challenges related to cost and large-scale efficiency. It is concluded that, despite the feasibility of CI techniques, their long-term impacts present significant uncertainties. Furthermore, the need for a global governance structure is highlighted to avoid unilateral actions that may bring disproportionate risks, especially to more vulnerable countries, such as those in the Global South. Therefore, more interdisciplinary studies are recommended to ensure that these technologies are applied in a safe and just manner.

**Keywords:** geoengineering, climate intervention, solar radiation modification, climate change, emission scenarios.

## Técnicas de Intervenção Climática: Prós e Contras

### RESUMO

As técnicas de intervenção climática (IC) são estratégias propostas para modificar o sistema climático da Terra, visando mitigar os efeitos adversos das mudanças climáticas. No cenário atual de crescente preocupação com o aquecimento global, essas técnicas surgem como potenciais complementos às medidas tradicionais de mitigação e adaptação. Este estudo tem como objetivo revisar as principais técnicas de IC, como a injeção de aerossóis estratosféricos, o branqueamento de nuvens marinhas e a remoção de dióxido de carbono (CO<sub>2</sub>). A metodologia adotada inclui uma revisão abrangente do estado da arte e de trabalhos de referência sobre o tema, avaliando a eficácia, os riscos e os desafios associados a cada técnica. Os resultados mostram que a injeção de aerossóis estratosféricos pode reduzir a temperatura global por meio do aumento do albedo terrestre, mas pode causar efeitos adversos, como mudanças nos regimes de precipitação, depleção de ozônio estratosférico, impactos no balanço radiativo e acidificação dos oceanos. Na mesma linha, o branqueamento de nuvens marinhas causa aumento do albedo. Por outro lado, as técnicas de remoção de CO<sub>2</sub> são vistas como soluções potenciais para a descarbonização, embora enfrentem desafios relacionados ao custo e à eficiência em larga escala. Conclui-se



que, apesar da viabilidade das técnicas de IC, seus impactos de longo prazo apresentam incertezas significativas. Além disso, destaca-se a necessidade de uma estrutura de governança global para evitar ações unilaterais que possam trazer riscos desproporcionais, especialmente para países mais vulneráveis, como os do Sul Global. Assim, recomendam-se mais estudos interdisciplinares para garantir que essas tecnologias sejam aplicadas de maneira segura e justa.

**Palavras-chave:** geoengenharia, intervenção climática, modificação da radiação solar, mudanças climáticas, cenários de emissão.

## Introduction

Climate change and its impacts are an increasingly recurring and relevant issue (Schaltegger et al., 2011; Princiotta, 2007). Evidence of these impacts includes intense extreme events in various parts of the globe, such as rising sea levels (Moore et al., 2011; Moore et al., 2013; Vousdoukas et al., 2018; Griggs & Reguero, 2021; Nienhuis et al., 2023), droughts (Strauss et al., 2013; Salvador et al., 2020; Gómez-Gómez et al., 2022; Yuan et al., 2023), increased risk of hurricanes (Grinsted et al., 2013; Mannshardt & Gilleland, 2013; Camelo et al., 2020; Rayner et al., 2022; Reed et al., 2022; Balaguru et al. 2023), and degradation of permafrost (Gao et al., 2013; Burke et al., 2020; Murton, 2021; Schuur et al., 2022). As the climate system warms, it is possible to see that points of no return may occur (McKay et al., 2022), and despite government measures to reduce emissions, such as the Paris Agreement (Rogelj et al., 2016), it is tough to achieve these goals and mitigate the effects conventionally (Rogelj et al., 2016; Millar et al., 2017; Tollefson, 2018; IPCC, 2018).

One of the proposals studied for tackling climate change is the so-called Climate Intervention (CI). This proposal consists of geoengineering techniques that aim, through human action, to intervene directly in the climate system to offset human-induced warming partially (Royal Society, 2009; Lawrence et al., 2018; Haywood et al., 2022a; UNEP, 2023). Although the definition seems simple, the strategies are socially sensitive, and the approaches depend on political action (Corner & Pidgeon, 2010; Sovacool, 2021).

The techniques explored by CI mainly consist of (i) stratospheric aerosol injection (Kravitz et al., 2011, 2013a, 2021; Visionsi et al., 2021, 2023); (ii) marine cloud brightening (Rasch et al., 2008; Jones et al., 2009, 2011; Mahfouz et al., 2023) and; (iii) carbon dioxide removal (Minx et al., 2018; Buck et al., 2020; Morrow et al., 2020). The following sections describe these techniques in more detail.

Initially called geoengineering or climate engineering, CI can be defined as the deliberate large-scale manipulation of the planetary environment to combat anthropogenic climate change (Robock, 2020). Despite being a relatively recent topic, the beginnings of geoengineering date back to the 1940s, when the possibility of seeding clouds with silver iodide was discovered to produce precipitation (Bruitjes, 1999).

Measures to deal with the adverse effects of climate change comprise a broad umbrella that includes different approaches such as mitigation, adaptation, and climate intervention (Brown, 2010). Mitigation targets the anthropogenic causes of climate change through actions to reduce greenhouse gas emissions or enhance carbon sinks (including transitioning to renewable energy, reducing deforestation, and promoting sustainable land use), while adaptation focuses on initiatives to reduce the vulnerability of natural and human systems to climate change impacts (IPCC, 2022). These actions include different types of adaptation, such as anticipatory, reactive, private, public, autonomous, and planned (Boucher et al., 2014). It seeks to increase the resilience of communities and ecosystems, and examples of this approach include building infrastructure resistant to extreme weather events, implementing early warning systems, diversifying crops, and developing water resource management plans (Forsyth, 2023).

On the other hand, CI comprises technological interventions that aim to alter natural systems to reduce climate change's effects (Baker, 2024). Generally, the technologies composing CI are divided into solar radiation modification (SRM) and removing carbon dioxide (American Meteorological Society, 2022).

SRM aims to reduce the amount of sunlight reaching the earth's surface or increase its reflective capacity. Among the technologies proposed for modifying solar radiation are the injection of aerosols into the stratosphere, the brightening of clouds, the placement of mirrors



and space umbrellas, covering the desert with reflective panels, covering glaciers in the Arctic with insulating material or reflective film, the use of white roofs etc. (Zhang et al., 2014). It is worth noting that these techniques do not seek to reduce the level of greenhouse gases in the atmosphere but to cool the earth's average temperature with greater solar reflection, so they can also alter global atmospheric circulation, with potential effects such as changing weather patterns and reducing rainfall (American Meteorological Society, 2022).

Carbon dioxide (CO<sub>2</sub>) removal aims to sequester CO<sub>2</sub> from the atmosphere and store it safely. Examples of this approach include: ocean fertilization (stimulating phytoplankton growth with iron, nitrogen or phosphorus to promote carbon removal in large marine quantities); deep carbon burial (technologies that use physical, biological or chemical processes to bury carbon in geological formations such as depleted oil reserves, coal mines or the deep seafloor); biochar (a product obtained by burning biomass through pyrolysis or carbonization, which is then buried in the ground); synthetic trees ("vacuum cleaners" of atmospheric CO<sub>2</sub> by converting sodium hydroxide into sodium carbonate, and then buried in the soil the extracted CO<sub>2</sub> in solid form); upwelling of ocean waters to cool surface waters and increase CO<sub>2</sub> absorption; adding calcium carbonate to the ocean to increase the alkalinity of the water and CO<sub>2</sub> removal; genetically modified algae and microbes to sequester high levels of CO<sub>2</sub> (Zhang et al., 2014).

Although these techniques directly reduce the concentration of greenhouse gases, they are only effective at removing a small amount of atmospheric CO<sub>2</sub> compared to cumulative anthropogenic emissions and may cause potential imbalances in food chains and marine ecosystems (Keller et al., 2014).

One of the biggest challenges facing CI is scientific uncertainty. Although computer simulations and preliminary studies suggest possible benefits (Figure 1), these models cannot capture the full complexity of the climate system and its long-term effects. It is not known, for example, how the injection of particles into the atmosphere could impact precipitation patterns, biodiversity, and entire ecosystems in different parts of the world (Tilmes et al., 2008; Pitari et al., 2014; Fasullo et al., 2018; Vioni et al., 2018; Trisos et al., 2018).

In addition to environmental risks, using CI without a proper understanding of its long-term effects can lead to severe socio-economic consequences. Regional climate change could

affect agriculture and water resources (Xia et al., 2014; Proctor et al., 2018). Developing countries, often more vulnerable to climate change, could be disproportionately affected, exacerbating global inequality (Abatayo et al., 2020). In this context, employing CI (especially without clear international agreements and the participation of the countries that could be most affected) could intensify geopolitical conflicts. Moreover, scientists, public policy experts, and environmentalists differ on the ethics and safety of these technologies (Reynolds, 2019; Schubert, 2024; Sovacool et al., 2024).

International regulation of CI faces major gaps, as current environmental treaties do not yet include specific norms for the field. Although conventions such as the Convention on Biological Diversity (CBD) (Du, 2017) and the London Convention and Protocol (Verlaan, 2013; Gailhofer et al., 2023) provide some guidance on activities such as ocean fertilization and encourage a precautionary approach, these documents do not present a cohesive and legally binding regulatory framework. The Paris Agreement, for example, promotes the use of preventive strategies and the consideration of geoengineering impacts but does not directly mention CI. In addition, the IPCC has already outlined these technologies' ethical and social aspects, reinforcing the need for transparent governance and assessing the risks to ecosystems and biodiversity (Reynolds, 2020).

This lack of regulatory uniformity creates geopolitical challenges since, without a clear legal framework, there is a risk of unilateral climate interventions that could affect vulnerable communities and ecosystems in different regions of the globe (Usman et al., 2022). The absence of guidelines on liability and compensation for the possible environmental and social damage caused by CI contributes to increased tensions and international disputes (Pezzoli et al., 2023; Sovacool et al., 2024). Implementing these techniques without consensus can affect the global climate balance, benefiting some countries and harming others (Reynolds, 2019; Abatayo et al., 2020).

CI remains little known and debated in scientific circles and the general public. Unlike widely accepted strategies, CI techniques still lack conclusive studies on long-term risks and impacts. In this context, the Degrees Initiative, formerly known as the Solar Radiation Modification Governance Initiative (SRMGI), emerged in 2010 as a response to discussions about the governance of solar geoengineering, primarily aimed at including scientists and communities from the Global South (Geoengineering Monitor, 2023;



Degrees Initiative, 2024). The initiative expanded its focus and, in 2021, reformulated itself to support research into SRM in developing countries. This support includes the Degrees Modelling Fund, which seeks to understand the effects of SRM on the climate of the Global South, and the Degrees Socio-Political Fund, launched to explore the social and political implications of these technologies in the region (Degrees Initiative, 2023).

This paper is part of the Brazilian team's contribution to the Degrees Initiative research project, aiming to provide a review of the leading CI techniques, including stratospheric aerosol

injection, marine cloud brightening, and carbon dioxide removal. The objective is to assess foundational studies that serve as references in the field and recent research highlighting the state-of-the-art advancements in these technologies. Its focus lies on solar radiation modification and carbon removal, examining their environmental and social impacts. Additionally, the study delves into governance challenges, emphasizing the need for a deeper understanding of the potential consequences of CI techniques, particularly for countries in the Global South.

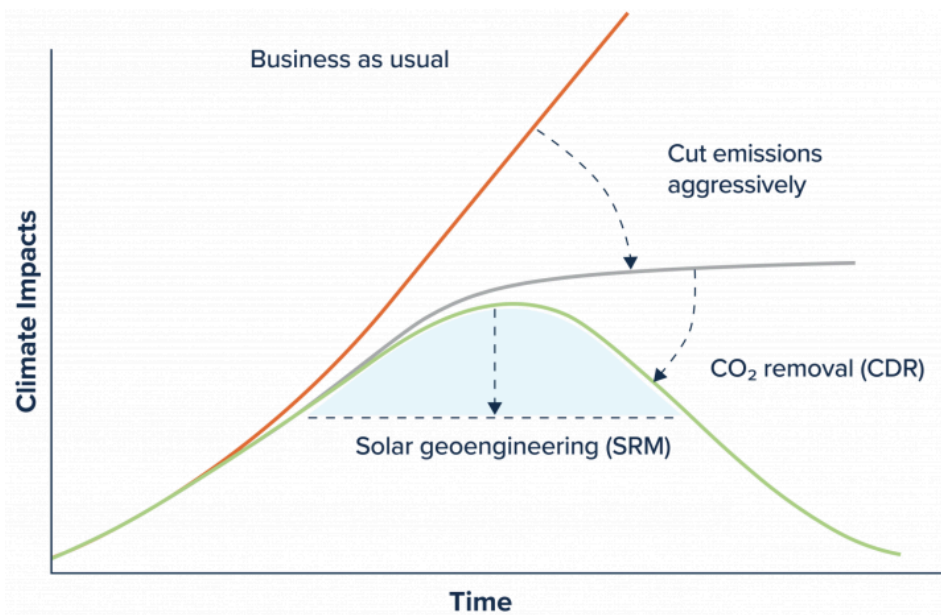


Figure 1. Napkin diagram showing approximately the role of Climate Intervention (CI) with the use of Solar Radiation Management (SRM) and CO<sub>2</sub> Removal (CDR) in climate risk management. Source: Degrees Initiative (2022).

## Material and Methods

This review assessed the scientific literature on CI techniques, focusing on stratospheric aerosol injection, marine cloud brightening, and carbon dioxide removal. The chosen papers were selected through various scientific research platforms, including Google Scholar, Web of Science, SciELO, Scopus, and Science.gov. The primary objective was to evaluate well-established works on the subject and recent studies highlighting state-of-the-art climate intervention techniques. Approximately 200 papers were analyzed, half published in the last five years, ensuring a balanced perspective between foundational research and contemporary advancements.

The analysis involved extracting key information from each selected study, covering the

efficacy of each technique, the most significant application results, and the associated challenges. Particular attention was given to climate modeling limitations, uncertainties regarding climate and biodiversity impacts, and political difficulties stemming from the lack of ethical and legal frameworks that include all countries potentially affected by CI techniques. This approach enabled a synthesis of current knowledge and the identification of critical areas needing further research and policy development.

## Types of Climate Intervention

Solar Radiation Modification (SRM)

*Stratospheric Aerosol Injection (SAI)*



According to the Intergovernmental Panel on Climate Change (IPCC), the natural component that can help cool the planet, albeit with uncertainties (Myhre et al., 2013), is the injection of sulfate aerosols into the stratosphere, as it contributes to increase the albedo (Figure 2, Dickinson, 1996; Robock et al., 2010; MacMartin et al., 2016; Kravitz et al., 2016). This technique arose from the knowledge that the global average air temperature decreases by around 0.5 °C between two and three years after volcanic eruptions (Hansen et al., 1996; Parker et al., 1996; Pesquisa Fapesp, 2024). These eruptions can increase the global albedo by between 5 and 10% (Minnis et al., 1993). Thus, SRM (Solar Radiation Management) aims to reduce the incident solar radiation to compensate for the increase in temperature due to greenhouse gas emissions.

In this regard, simulations like the GeoMIP6, from the Coupled Model Intercomparison Project (CMIP6), provide different projections, such as G6solar, which simulates the attenuation of the amount of incident solar radiation artificially reduced, and G6sulfur, which simulates the reduction of the average radiative forcing with stratospheric sulfate aerosols (Kravitz et al., 2015). In addition, Marine Cloud Brightening (MCB) experiments such as G4Sea-Salt evaluate the impact of the technique by injecting sea salt between the latitudes of 30°S and 30°N, noting that the direct effect of aerosols can contribute significantly to the modeled cooling (Kravitz et al., 2013b; Ahlm et al., 2017).

Moreover, the Geoengineering Large Ensemble (GLENS; Tilmes et al., 2018) project simulates sulfur dioxide (SO<sub>2</sub>) injections at an altitude of ~25 km at four different latitudes (30°S, 15°S, 15°N and 30°N) at 180°E to maintain the global average surface temperature, the inter-hemispheric surface temperature gradient and the surface temperature gradient from the equator to the pole at 2020 values, under the Representative Concentration Pathway 8.5 (RCP8.5) scenario. Similarly, the Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection (ARISE) project simulates SO<sub>2</sub> injections at the exact locations as GLENS (at around ~21.6 km altitude) but keeps the global average temperature close to 1.5 °C above pre-industrial times at the end of the century.

SAI research encompasses both indoor studies which focus on climate modeling (and the analysis of natural analogs like volcanic eruptions) and outdoor experiments that involve injecting

particles into the atmosphere to modify the Earth's albedo (Robock et al., 2012).

Climate models suggest that SAI can disperse around 1% of incident solar radiation, which would complement other climate risk reduction measures such as cutting emissions, CO<sub>2</sub> removal, and adaptation (Irvine et al., 2016, 2019; MacMartin & Kravitz, 2016; Parson et al., 2024). Modeling-based studies indicate that SAI can mitigate climate change impacts by offsetting different effects such as the acceleration of the hydrological cycle (Kravitz et al., 2013a; Tilmes et al., 2013), the melting of glaciers (Moore et al., 2014; Zhao et al., 2017), the intensity or frequency of extreme events (Curry et al., 2014; Dagon & Schrag, 2017) and the intensity of tropical cyclones (Moore et al., 2015; Irvine et al., 2019).

However, despite its low cost (Barrett, 2008; Moriyama et al., 2017) and studies suggesting that SAI can promote a climate close to the reference period in almost all regions (Matthews & Caldeira, 2007; Ban-Weiss & Caldeira, 2010; Kravitz et al., 2011, 2014; Tilmes et al., 2014; MacMartin et al., 2018; Irvine et al., 2019; Kravitz & MacMartin, 2020), its use still does not guarantee to offset for changes in temperature and precipitation patterns across the globe (Moreno-Cruz et al., 2012; MacMartin et al., 2014; Kravitz et al., 2014; Kravitz & MacMartin, 2020). For example, SAI can alter precipitation patterns, intensifying negative impacts resulting from El Niño events (Saxler et al., 2015), as well as affecting the monsoon cycle (Robock, 2008; Saxler et al., 2015; Proelss & Steenkamp, 2023).

Furthermore, different SAI applications produce different regional effects, so while SAI in high latitudes cools the polar regions and impacts glaciers (Kravitz et al., 2017; Zhao et al., 2017; Kravitz & MacMartin, 2020), its use in only one hemisphere cools the region and can promote changes in tropical precipitation (Haywood et al., 2013; Kravitz & MacMartin, 2020). Additionally, potential adverse effects of SAI include ecosystem changes (Trisos et al., 2018; Dagon & Schrag, 2019; McDonald, 2022); stratospheric ozone depletion and changes in ultraviolet radiation (Tilmes et al., 2008; Pitari et al., 2014; Robrecht et al., 2021; Tilmes et al., 2022; Moch et al., 2023); interactions with cirrus clouds and effects on the radiative balance (Visioni et al., 2018); ocean acidification (Fasullo et al., 2018); intensification of acid rain (Visioni et al., 2018); effects on agriculture (Xia et al., 2014; Proctor et al., 2018) and health (Robock et al., 2009; Heckendorn et al., 2009; Irvine et al., 2017). Other lesser-known



possible effects include rapid warming with the abrupt cessation of SAI application, reduced solar electricity generation, and effects on the electrical properties of the stratosphere and remote sensing (Robock, 2020). A more comprehensive overview of the positive and negative impacts of SAI (as well as other SRM techniques) can be found in Sovacool et al. (2023).

International projects have provided comparative projections with and without SRM. In general, these simulations project a reduction in global warming and fewer extreme events (Barnes et al., 2022; Richter et al., 2022; Tye et al., 2022; Haywood et al., 2022b; Hueholt et al., 2024) in temperature (Ricke et al., 2010) and precipitation (Bala et al., 2008; Robock et al., 2009; Tilmes et al., 2013). At the regional level, some studies have assessed the impacts of implementing SRM in Africa (Karami et al., 2020: storm trajectory; Pinto et al., 2020: mean and extreme values of temperature and precipitation; Obahoundje et al., 2023: dry and wet extremes), North and Central America (Shields et al., 2022: impacts on atmospheric rivers) and Asia (Kuswanto et al., 2021: extreme temperature indices; Tan et al., 2023: hydroclimatic extremes). Despite this, studies for South America are still scarce. The few studies include, for example, that by Camilloni et al. (2022), which evaluated the impacts of SRM on the hydroclimate of the La Plata Basin, where the intervention can decrease temperature extremes in the basin.

Recently, the first study led by the Brazilian Degrees Initiative team (Degrees Initiative, 2023; Reboita et al., 2024), in collaboration with researchers from South Africa, investigated how SAI and climate change affect extratropical cyclones in the Southern Hemisphere. The results indicate that SAI could mitigate change effects on cyclone intensity, keeping it close to current levels. However, SAI also complicates the systems' behavior. For example, although both scenarios (with and without SAI) suggest a change in the spatial pattern of cyclones, the scenario with SAI indicates a minor reduction in the frequency of systems (Reboita et al., 2024). Thus, the authors highlight the need for further research to understand the implications of SAI on cyclone behavior.

SAI research and implementation raise complex ethical and political dilemmas. Several international treaties and conventions touch on aspects of SRM but do not provide a specific and comprehensive regulatory framework (Bodansky, 2013; Dupuy et al., 2021; Parson & Reynolds, 2021; Felgenhauer et al., 2022). The Convention

on Biological Diversity recommended that, without global control mechanisms, no geoengineering activity that could affect biodiversity should be carried out without a sound scientific basis (UNEP, 2010).

The London Protocol banned marine geoengineering activities, but its applicability to SRM remains uncertain (Parson & Keith, 2024). The Climate Overshoot Commission has suggested a moratorium on large-scale interventions until there is greater clarity on the risks (Climate Overshoot Commission, 2023), while the IPCC has highlighted ethical and political implications of SRM, including concerns about climate justice and governance (IPCC, 2018). Organizations such as UNESCO and the United Nations Environment Programme (UNEP) have also promoted discussions but have yet to adopt concrete guidelines (Parson and Keith, 2024). Thus, although SRM remains an area of growing interest, the absence of an effective international governance regime makes it difficult to make informed and secure decisions about its research and possible implementation.

#### *Marine Cloud Brightening (MCB)*

Similar to SAI, marine cloud brightening (MCB), also known as “cloud albedo enhancement”, is a SRM technique that aims to partially increase atmospheric albedo by reflecting sunlight into space to compensate for atmospheric warming (Latham et al., 2012). The overall cost of MCB is estimated to be similar to that of SAI and is relatively low compared to the costs of mitigating emissions and climate damages (NAS, 2021; Duffey et al., 2023).

The MCB technique consists of injecting sea salt particles into the atmosphere to increase the number of water droplets in low clouds over the oceans, especially in regions with stratocumulus clouds (Figure 2, Latham et al., 2008; Caldeira et al., 2013). Low clouds are excellent means of increasing albedo, as they reflect part of the incident radiation. The more droplets in a cloud, the greater the reflectivity, helping to cool the planet.

MCB increases reflectivity by applying aerosol's first and second indirect effects on clouds (Minnuno et al., 2023). The first indirect effect involves increasing the concentration of droplets in the cloud to increase its optical thickness and ability to reflect more shortwave radiation (Ahlm et al., 2017). The second indirect effect of aerosol is to increase the lifetime of cloud cover, according to the hypothesis that smaller droplets take longer to coalesce into



droplets larger enough to precipitate out of clouds (Jones & Haywood, 2012; Horowitz et al., 2020). Thus, understanding the MCB is intrinsically linked to addressing the uncertainties of aerosol-cloud interactions (Parson & Keith, 2024).

MCB could be used more regionally due to the short half-life of tropospheric aerosols (Bala et al., 2011; Haywood et al., 2023) and the area of cloud cover. In addition, studies indicate that there is dependence on the region applied, which can affect different climate regions due to teleconnection effects (Bala et al., 2011; Stjern et al., 2018; Ahlm et al., 2017; Diamond et al., 2022; Odoulami et al., 2024). Potential regions for MCB application include colder areas of the subtropical and mid-latitude oceans (Ahlm et al., 2017).

Global climate models (GCMs) simulations indicate that increasing the concentration of droplets in marine clouds by a few hundred per cubic centimeter could generate a negative radiative forcing capable of offsetting the warming caused by CO<sub>2</sub> doubling (Latham et al., 2012; Minnuno et al., 2023).

However, the effectiveness of MCB is controversial, mainly due to its limited scalability. Studies suggest this technique is only viable in regions with marine stratocumulus cloud formation, covering only around 10% of the Earth's surface (Partanen et al., 2016). Even so, simulations of GCMs show that the MCB application, even in such a restricted area, can have significant climate impacts (Kim et al., 2020; Zhao et al., 2021; Minnuno et al., 2023).

Increasing the number of cloud condensation nuclei (CCN) in marine clouds while keeping the water content constant tends to increase the cloud's albedo, i.e., its ability to reflect solar radiation (Parson & Keith, 2024). However, the net effect of MCB can vary significantly depending on local meteorological conditions, increasing albedo in some situations but having little impact or even reducing albedo in others (Feingold et al., 2024; Parson & Keith, 2024).

Parkes et al. (2012) used a GCM to assess the effects of MCB in three areas with persistent marine stratocumulus clouds located in mid-latitudes over the North Pacific, South Pacific, and South Atlantic. The results showed an average reduction of 0.8 °C in the polar regions' global temperature, which helps mitigate polar amplification by decreasing ice loss at the South Pole and increasing ice cover at the North Pole. These findings show that applying negative radiative forcing exclusively over limited ocean regions can significantly reduce polar ice melt and preserve sea ice.

In addition, MCB can reduce temperature anomalies, slow polar ice loss, and reduce coral bleaching (Latham et al., 2014). Still, it can also increase evaporation, cloud formation, and precipitation in low-latitude land regions (Zhang et al., 2014).

A study has shown that reducing cloud droplet size uniformly over all oceans to counteract warming due to CO<sub>2</sub> doubling results in a 1.3% reduction in global precipitation but increases runoff by 7.5%, especially in tropical areas (Bala et al., 2011). In contrast, increasing the albedo in terrestrial regions causes a more significant decrease in precipitation (13.4%) and runoff (22.3%). Therefore, changing the albedo in the oceans affects the global hydrological cycle less than similar changes over land (Bala et al., 2011; Zhang et al., 2014).

Regarding the Arctic polar region, the MCB can generate a negative local radiative forcing of up to 11 W/m<sup>2</sup>, although the presence of ice particles reduces its effectiveness (Kravitz et al., 2014). However, to preserve sea ice under the RCP8.5 high emissions scenario, a much larger forcing would be required, especially north of 60°N, due to compensatory heat fluxes towards the poles (Tilmes et al., 2014; Duffey et al., 2023).

A recent study concluded that MCB can reduce the risk of heat waves by up to 55% in the remote mid-latitudes and 16% in the near subtropics (Wan et al., 2024). However, under projected warming conditions for the middle of the century, this technique has reduced effectiveness or even increased heat stress in the western United States and globally. These results indicate that interventions that work under current scenarios may not be equally effective as those under climate change.

Additionally, other less understood possible adverse effects of the MCB include stratospheric ozone depletion, negative impacts on marine ecosystems, and uneven cooling effects, potentially exacerbating climate inequalities between regions (Haywood et al., 2023; Ricke et al., 2023; Sovacool et al., 2023).

In this context of scientific uncertainty, GeoMIP has implemented different phases of MCB experiments (Kravitz et al., 2013b): the first phase simulates a uniform increase in ocean albedo to compensate for the effect of a quadrupling of CO<sub>2</sub> compared to pre-industrial levels; the second raises the concentration of droplets in all low-altitude marine clouds to reduce part of the radiative forcing in an RCP4.5 scenario; the third phase injects sea salt aerosols into the boundary layer between 30°S and 30°N to neutralize 2 W/m<sup>2</sup> of radiative forcing. These



tests, particularly in Phase 2 of GeoMIP, seek to understand how the increased concentration of CCN affects cloud albedo, using multiple climate models to ensure greater comprehensiveness in the results (Stjern et al., 2018).

Conducting MCB experiments raises complex political and ethical issues, mainly due to the absence of a transparent system of international governance to regulate such interventions. Morgan and Ricke (2010) suggest creating a “permitted zone” for such experiments, which should be carefully defined to ensure no lasting climate effects. However, this definition is still vague, especially regarding complex impacts such as changes in sea surface temperature and potential consequences for marine ecosystems.

The central argument is that experiments should be conducted cautiously, considering the potential risks and recognizing that failure to act could lead to even more severe consequences due to global warming (Preston, 2013; Rayner et al., 2013). Therefore, this research must be carried out transparently to increase our understanding of climate change and its possible mitigators.

### *Carbon Dioxide Removal (CDR)*

Climate intervention through the removal of carbon dioxide (CO<sub>2</sub>), known as Carbon Dioxide Removal (CDR), involves the permanent removal of carbon dioxide from the atmosphere to reduce the concentration of greenhouse gases and thus mitigate the effects of climate change (Climeworks, 2023; Parry, 2022; Mistry et al., 2023). CDR techniques include methods such as removing greenhouse gas from the atmosphere and storing them in natural “carbon sinks” such as forests and soils or through technological approaches like reforestation, bioenergy with carbon capture and storage, and direct air capture (Figure 2, IPCC, 2022; Carbon Market Watch, 2024). Although these approaches could bring global benefits by directly tackling the cause of global warming, there are still uncertainties about their feasibility on a large scale and the possible environmental and social impacts that could arise.

Among the various CDR techniques, each has its peculiarities, benefits, and challenges. Among the primary methods are reforestation and afforestation, which promote planting trees in deforested areas or regions with no forest cover (Denton et al., 2022). Trees absorb CO<sub>2</sub> from the atmosphere during their growth, storing it in their biomass for decades or more (Sovacool et al., 2023). Although effective, these practices can compete for land and water with agricultural

activities, and the release of stored carbon can occur in cases of improper burning or harvesting (García-Quijano et al., 2007; Wani et al., 2012; Shi et al., 2013; Sovacool et al., 2023).

Ocean fertilization is a technique that adds nutrients such as iron or urea to the ocean’s euphotic zone to stimulate phytoplankton growth. This practice aims to increase the absorption of atmospheric and marine CO<sub>2</sub>, reducing environmental and ocean temperatures (Minnuno et al., 2023). Studies indicate that fertilization can promote carbon sequestration by encouraging the formation of organic detritus that sinks into deep waters (Williamson et al., 2012; McGee et al., 2018). However, only a tiny fraction of this carbon reaches the ocean floor, most of which is re-emitted to the atmosphere due to biomass degradation (Keith, 2000; Macreadie et al., 2019). Challenges such as carbon leakage and the lack of reliable models still limit its application on a large scale (Lampitt et al., 2008).

Complementary initiatives, such as increasing ocean alkalinity and restoring coastal ecosystems (such as mangroves, salt marshes, and seagrass beds), known as blue carbon, have also gained prominence (Zhang et al., 2014; Bach et al., 2019; Sovacool et al., 2023). These methods intensify CO<sub>2</sub> absorption and act as important carbon sinks (Sabine et al., 2004). However, ocean fertilization and these strategies require further research to assess their effectiveness and long-term impacts (Minnuno et al., 2023).

Direct air capture with carbon storage (DACCS) uses large fans to remove CO<sub>2</sub> directly from the atmosphere and store it safely in underground geological formations (Jonge et al., 2019; Deutz & Bardow, 2021; Terlouw et al., 2021). Although this technology does not require large land areas, it is energy-intensive and still has high implementation costs (Bui et al., 2018; Fasihi et al., 2019). Bioenergy technologies with carbon capture and storage (BECCS) combine biomass cultivation to generate energy by capturing CO<sub>2</sub> emitted during burning and storing it underground (Kemper, 2015; Fajardy & Dowell, 2017). However, both approaches face similar challenges, such as the need for suitable geological formations and competition for resources such as land and water (Terlouw et al., 2021).

Chemical weathering is a technique that seeks to accelerate natural processes of CO<sub>2</sub> absorption by rocks by crushing them and scattering the fragments on agricultural land or coastal areas (Hartmann et al., 2013; Bach et al., 2019). This method offers long-term storage in the oceans, but there are uncertainties about its feasibility on a large scale and the potential



environmental impacts of rock mining (Hartmann et al., 2013; Taylor et al., 2016; Bach et al., 2019).

Agricultural practices that promote soil carbon sequestration, such as crop rotation and increased vegetation cover, also represent a viable option (Sovacool et al., 2023). These practices can improve soil quality while storing carbon for decades, but their efficiency depends on consistent adherence by farmers and land managers.

Finally, the production of biochar involves converting organic material into a type of charcoal by heating it in low oxygen (Lehmann et al., 2011; Wang et al., 2020). This material can be mixed into the soil, storing carbon for long periods and improving fertility (Sun Cha et al., 2016). Although promising, biochar competes with other uses for biomass, such as energy or fuels (Sovacool et al., 2023).

In summary, CDR technologies have great potential to complement climate mitigation

efforts, but each approach has specific limitations and challenges. Their large-scale adoption will depend on technological innovations, financial investments, and a global commitment to sustainable solutions to the climate crisis. However, the assessment by Mistry et al. (2023) provides further evidence that CDR is crucial to decarbonizing the global economy and achieving the net-zero targets set by the Paris Agreement.

Despite carbon capture machines, significant challenges exist, such as high implementation and operating costs and low efficiency when dealing with the large amounts of CO<sub>2</sub> dispersed in the atmosphere due to their immense vertical size. These challenges make capturing large quantities a costly process and difficult to scale up, limiting the effectiveness of this technology in large-scale climate mitigation (Budinis et al., 2018).

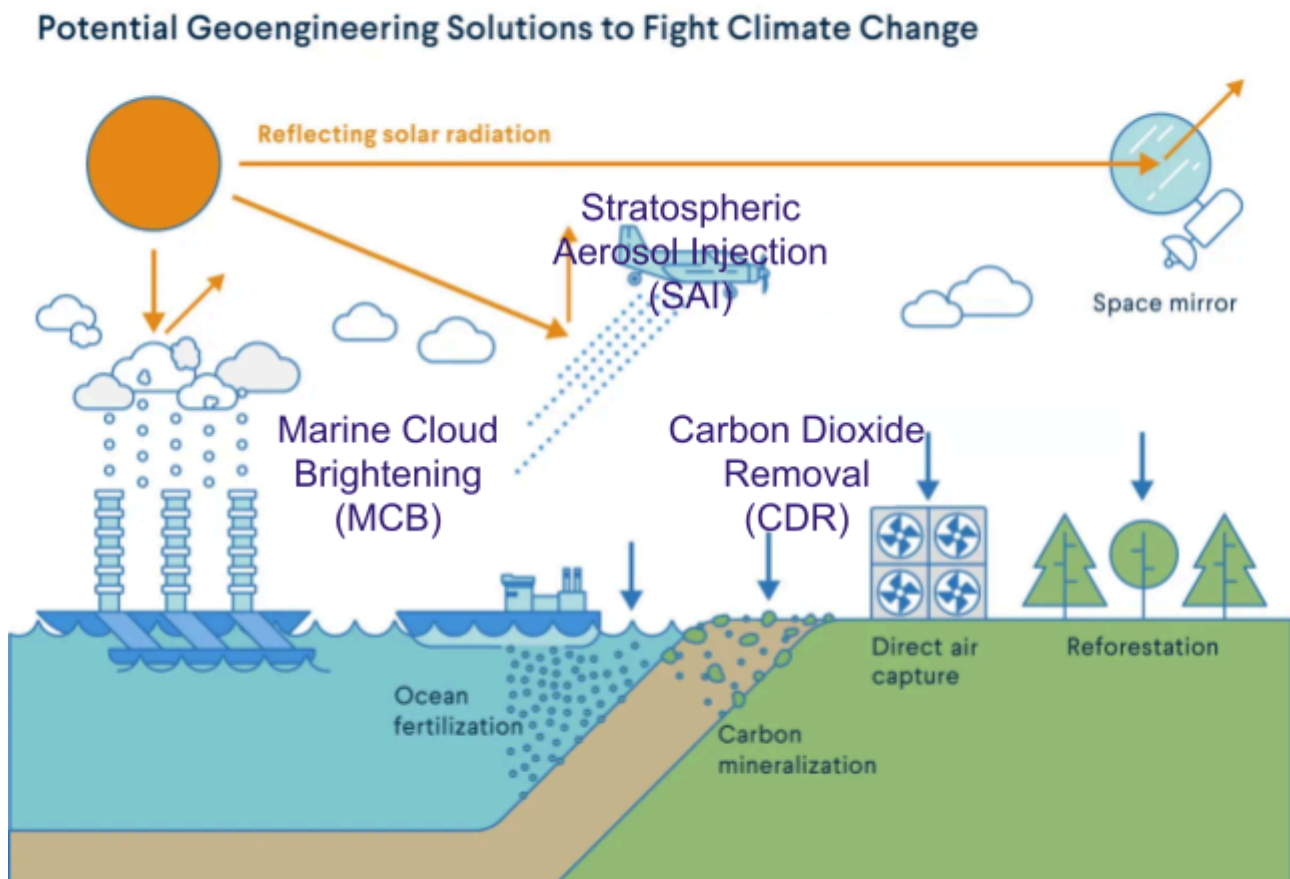


Figure 2: Overview of the main Climate Intervention (CI) techniques. These include Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB) and different forms of CO<sub>2</sub> Removal (CDR). Source: EcoEngineer (2024).



## Modeling Climate Intervention

Although outdoor research is also deemed necessary, climate models are essential for simulating the effects of CI techniques like SAI and MCB, requiring large-scale, long-term implementations due to the climate system's complexity, with research relying on sophisticated computer models and supercomputers to reproduce Earth's system behavior and assess future climate impacts (Robock et al., 2020).

The techniques are incorporated through parameterized representations based on observations and experiments using advanced technologies and international collaborative programs (Kravitz et al., 2021). GeoMIP (GeoMIP, 2024) was created to standardize geoengineering experiments and resolve inconsistencies between initial studies. Initially, its research involved climate simulations by reducing the solar constant and applying SAI later expanded to other techniques such as MCB (Visioni et al., 2023). Since its creation, GeoMIP has produced more than 100 studies that analyze the impacts of these experiments on climate, ecosystems, and human societies (Visioni et al., 2023; GeoMIP, 2024).

In the United States, institutions such as NCAR, NOAA, and NASA contribute resources and expertise in climate modeling and land surface impacts (Robock et al., 2020). Despite advances, funding for geoengineering research is limited, with a prevalence of studies carried out in developed countries (Brown, 2010) and increasing dependence on private sources (Necheles et al., 2018).

Climate simulations face significant limitations, particularly concerning the accuracy and predictability of the results (Kravitz et al., 2021). Due to the limitations of climate models and the scarcity of observations, reducing uncertainties related to radiative forcing and climate response is challenging (Kravitz et al., 2016). Climate feedbacks, including cloud-aerosol interactions and changes in the hydrological cycle, introduce complexity and uncertainty to projections, while the models' spatial and temporal resolutions remain insufficient to fully capture local phenomena and long-term impacts (Kravitz et al., 2016, 2021).

A recent approach is integrating explicit feedback into climate models to adjust geoengineering techniques in real-time (Kravitz et al., 2016). Based on control theory, this approach makes it possible to monitor the state of the climate and adjust interventions according to the observed climate response, minimizing

uncertainties (MacMartin et al., 2013; Kravitz et al., 2016).

Recent advances in the field of CI include using high-resolution models to capture detailed patterns of atmospheric circulation and aerosol-cloud interactions and integrated studies on ecological and social impacts (Kravitz et al., 2021). Despite advances, interdisciplinary research is urgently needed to address knowledge gaps, such as environmental effects at local scales and the ethical risks associated with implementing these techniques.

## Conclusion

This article reviewed the leading climate intervention techniques, including stratospheric aerosol injection, marine cloud brightening, and CO<sub>2</sub> removal, and highlighted the essential role of climate modeling in understanding their effects. It discussed how these approaches seek to mitigate climate change impacts, such as global warming and alterations in the hydrological cycle, while facing significant challenges, such as uncertainties in climate feedback, limitations in modeling complex processes, and ethical and social concerns.

Recent advances in climate modeling, driven by initiatives such as GeoMIP, have provided valuable insights into these interventions' regional and global impacts. These contributions include improvements in model resolution, greater integration between climate and ecological studies, and exploring combinations between climate mitigation and adaptation techniques, representing a promising field for the future.

However, geoengineering techniques still involve many uncertainties in various spheres, including scientific, ethical, political, economic, and social. These uncertainties reinforce the need for more interdisciplinary research and global discussions to ensure that, if implemented, these solutions are applied responsibly, minimizing risks and maximizing benefits.

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## 6. RESPONSE OF THE SOUTHERN HEMISPHERE EXTRATROPICAL CYCLONE CLIMATOLOGY TO CLIMATE INTERVENTION WITH STRATOSPHERIC AEROSOL INJECTION

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# Response of the Southern Hemisphere extratropical cyclone climatology to climate intervention with stratospheric aerosol injection

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## Response of the Southern Hemisphere Extratropical Cyclone Climatology to Climate Intervention with Stratospheric Aerosol Injection

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### Abstract

Little is known about how climate intervention through stratospheric aerosol injection (SAI) may affect the climatology of the Southern Hemisphere extratropical cyclones under warming scenarios. To address this knowledge gap, we tracked extratropical cyclones from 2015 to 2099 in a set of projections of three international projects: the Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection (ARISE), the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS), and the Geoengineering Model Intercomparison Project (GeoMIP/G6sulfur). Comparisons were performed between no-SAI and SAI scenarios as well as between different timeslices and their reference period (2015-2024). Among the findings, both no-SAI and SAI project a decrease in cyclone frequency towards the end of the century although weaker under SAI scenarios. On the other hand, cyclones tend to be stronger under no-SAI scenarios while keeping their intensity more similar to the reference period under SAI scenarios. This means that under SAI scenarios the climatology of cyclones is less affected by global warming than under no-SAI. Other features of these systems, such as travelling distance, lifetime, and mean velocity show small differences between no-SAI and SAI scenarios and between reference and future periods.

**Keywords:** stratospheric aerosol injection, solar climate intervention, extratropical cyclones, future projections, Southern Hemisphere



## Introduction

Extratropical cyclones are a response of the atmosphere to attain thermal equilibrium. They develop mainly due to near-surface horizontal temperature gradients, a predominant feature in mid-latitudes, and transport heat and water vapor towards the poles and cold and dry air towards the tropics (Peixoto and Oort, 1992). Despite their important role in the climatic system, many cyclones can also cause extreme weather events such as intense precipitation, strong winds, and abrupt temperature changes. Over the ocean, air-sea momentum exchange is responsible for maritime agitation, which can lead to the occurrence of storm surges and giant waves, causing disruptions to navigation, operations on oil platforms, and the destruction of coastal ecosystems and infrastructure (Rocha et al., 2004, Gramcianivov et al., 2020, Faria et al., 2023).

In extensive databases, such as reanalysis and model outputs, cyclone climatologies are obtained using objective methods based on the mean sea level pressure (MSLP), relative vorticity, or geopotential height (Walker et al., 2020). For the Southern Hemisphere, centenary reanalysis (ERA20C) from 1900 to 2010 indicates a negative trend in the frequency of extratropical cyclones (Marrafon et al., 2021). This signal is also projected in future warming scenarios by global and regional climate models (Bengtsson et al., 2009, Michaelis et al. 2017, Reboita et al., 2021a, Sinclair et al., 2020, de Jesus et al., 2021; Priestley and Catto, 2022). In contrast, the frequency of stronger cyclones (systems that reach central pressure lower than 980 hPa in some period of their lifecycle) increases in reanalyses (Pezza and Ambrizzi, 2006, Reboita et al., 2015) and in climate projections (Reboita et al., 2015, 2021a,b). For instance, along the eastern coast of South America the frequency of explosive cyclones (i.e. cyclones with pressure dropping by  $\sim 24$  hPa/24 h) is projected to increase mainly near Uruguay and south of Brazil (Reboita et al., 2021b), which can cause even more damage to coastal areas.

Despite significant progress in understanding the role of climate change in the climatology of extratropical cyclones, there is a lack of studies focusing on the impact of climate intervention on these systems. Climate intervention (also known as climate geoengineering) appears as an aggressive approach to reduce global warming since the climate system is intentionally modified. It involves deliberate manipulation of the physical, chemical, or biological processes of the Earth system with the intention of tempering the harmful effects of anthropogenic greenhouse gas emissions (AMS, 2022). Climate intervention encompasses two categories: 1) removing CO<sub>2</sub> from the atmosphere, known as Carbon Dioxide Removal (CDR), and 2) reflecting sunlight, known as Solar Radiation Modification (SRM) or solar geoengineering. One of SRM approaches involves the injection of sulfate aerosols (or their precursor sulfur dioxide - SO<sub>2</sub>) into the stratosphere to enhance solar energy reflection; this approach is known in the literature as SAI (Stratospheric Aerosol Injection). By reducing the amount of solar energy entering the climate system, the Earth's surface would cool on average. This concept draws from observations of past volcanic eruptions. For instance, the eruption of Mount Pinatubo in 1991 injected 20 million tons of SO<sub>2</sub> into the stratosphere, resulting in increased sunlight reflection and a globally averaged surface air temperature cooling of  $\sim 0.3^{\circ}\text{C}$  for a period of 3 years (National Research Council, 2015).

Both categories of climate intervention present risks and deserve much study before their real application (Robock et al., 2009; Dykema et al., 2014; National Research Council, 2015;



AMS, 2022; Ricke et al., 2023). One way to assess the impact of climate intervention approaches on the climate system (basic variables and atmospheric systems) is through climate simulations/projections. Three international projects have conducted simulations/projections by using SAI and have made the data available: the Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection (ARISE; Richter et al., 2022); the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS; Tilmes et al., 2018), and the Geoengineering Model Intercomparison Project (GeoMIP) with the experiment G6sulfur; Vioni et al., 2021). These experiments have some differences such as the simulated period, greenhouse gas scenarios, and the region where the particles are introduced in the stratosphere (Irvine et al., 2016); more details about them are provided in Section 2. Currently, the data of these three projects are largely used for assessing the potential impact of SAI on the climate system (e.g. Bednarz et al., 2022; Camilloni et al., 2022; Patel et al., 2023).

While a general result is that SAI could effectively limit global warming (Moore et al., 2015; Irvine et al., 2019; Krishnamohan et al., 2019), the impacts on various aspects of the climate system, such as in water balance and in the lifecycle of the atmospheric systems, remain unclear due to the different stratospheric processes and formulations of SO<sub>2</sub> injection in climate models (Kravitz et al., 2014; Jiang et al., 2019). For instance, Rickie et al. (2023) reported that “The expected hydrological effects of reducing insolation are among the most uncertain and consequential impacts of solar geoengineering”.

In terms of atmospheric systems without considering SAI, Chand et al. (2022) found a negative trend in the frequency of tropical cyclones across all ocean basins using centenary reanalysis. This trend is also consistent in climate projections under warming scenarios, along with an increase in the tropical cyclone’s intensity (Vecchi and Soden, 2007; Walsh et al., 2015). Under SAI scenarios, studies such as that of Jones et al. (2017) have shown that aerosol enhancements confined to a single hemisphere could effectively modulate North Atlantic tropical cyclone activity. For instance, sulfate SAI in the Southern Hemisphere would enhance tropical cyclone frequency relative to global aerosol injection, and vice-versa for injection in the Northern Hemisphere.

Specifically for extratropical cyclones, the authors do not know of studies applying the identification and tracking of individual cyclones aiming to compare scenarios with and without SAI. Until this date, the only two published studies on extratropical cyclones analyzed environmental conditions: one based on mean available potential energy (Gertler et al., 2020) and the other on Rossby wave packets (Karami et al., 2020). Gertler et al. (2020) investigated scenarios with continued preindustrial conditions, 4xCO<sub>2</sub>, and 4xCO<sub>2</sub> plus SAI from GeoMIP. Under 4xCO<sub>2</sub>, storm tracks in the Northern Hemisphere are projected to weaken somewhat and greatly strengthen in the Southern Hemisphere. On the other hand, under the climate intervention scenario the storm tracks weaken in both hemispheres, but in the Northern Hemisphere the weakening is comparable to that from 4xCO<sub>2</sub>. Karami et al. (2020) investigated the storm track response to the RCP8.5 scenario and to this same scenario plus sulfate SAI over the Middle East and North Africa region between 2050 and 2070. They compared GLENS projections with the present climate, and the main findings are: (a) increasing greenhouse gas concentrations result in the northward (poleward) shift of the storm tracks in all seasons, (b) under SAI scenario, there is a partial offset of the



poleward shift of the storm tracks seen in the RCP8.5, consequently contributing to reducing the precipitation in the study area.

As at mid-latitudes the weather is primarily controlled by the development of extratropical cyclones and their associated fronts (Catto and Pfahl 2013; Eisenstein et al. 2023), it is crucial to explore the consequences of SAI on the climatology of these systems under warming scenario using a different approach from the previously described studies. Hence, this study aims to address the existing research gap by assessing how the main features of extratropical cyclone's climatology (frequency, intensity, trajectory etc.) over the Southern Hemisphere could change in the future under SAI scenarios provided by ARISE, GLENS, and GeoMIP/G6sulfur projects.

## 2 Methodology

### 2.1 Study Area and Data

The study area encompasses the latitudes southern 20°S to avoid the inclusion of tropical cyclones in the climatology (Reboita et al., 2015). Extratropical cyclones are identified using Mean Sea Level Pressure (MSLP) at every 6 hours (0000, 0600, 1200 and 1800 UTC) from three climate modeling projects: ARISE, GLENS, and GeoMIP/G6sulfur (**Table 1**).

ARISE projections were carried out with CESM2 global climate model (GCM), GLENS with CESM1 and GeoMIP/G6sulfur with MPI-ESM1-2-LR (**Table 1**). From each GCM we obtained three members without SO<sub>2</sub> SAI (hereafter called no-SAI) and with SO<sub>2</sub> SAI (hereafter called SAI). As these projections are well-documented in the literature, just a summary of their main information (such as number of members and design of the experiments) is provided here. Considering the no-SAI projections, they follow different emission pathways, i.e., ARISE is under SSP2-4.5, GLENS is under RCP8.5 and GeoMIP is under SSP5-8.5 (hereafter ARISE<sub>SSP2-4.5</sub>, GLENS<sub>RCP8.5</sub> and GeoMIP<sub>SSP5-8.5</sub>). Although SAI projections in ARISE are named by ARISE-SAI-1.5 and in GeoMIP we are just using the G6sulfur experiment, in the present study, for brevity, we call these dataset only by ARISE<sub>SAI</sub>, GLENS<sub>SAI</sub> and GeoMIP<sub>SAI</sub>. In the three projects, SAI projections consider the SO<sub>2</sub> injection into the lower stratosphere at four off-equatorial locations (30°S, 15°S, 15°N, and 30°N) in ARISE<sub>SAI</sub> and GLENS<sub>SAI</sub>, and within a range of 10°N and 10°S across the single longitude band of 0° in GeoMIP-SAI. Injection amounts at each latitude in the three experiments are controlled by a feedback algorithm, which aims to maintain the global mean surface temperature and its equator-to-pole and inter-hemispheric gradients at the baseline levels (Kravitz et al., 2017). In ARISE<sub>SAI</sub> the baseline period was defined as the 2020–2039 mean, corresponding to the likely period when the real world will reach 1.5 K above pre-industrial conditions (MacMartin et al., 2022; Tebaldi et al., 2021). In GLENS<sub>SAI</sub>, the baseline period used in the feedback algorithm was 2010–2030 mean.

As the projects differ in relation to the greenhouse gas emission scenarios (**Table 1**), it leads to a different magnitude of SAI (Richter et al., 2022), and also a distinct spatial distribution of the aerosols in the simulations (Bednarz et al., 2022; Fasullo and Richter, 2022). For instance, Bednarz et al. (2022) compared the distribution of SO<sub>2</sub> injections in ARISE<sub>SAI</sub> and GLENS<sub>SAI</sub> and found that GLENS<sub>SAI</sub> has the largest concentrations of sulfate in the North



Hemisphere tropics while  $ARISE_{SAI}$  in the Southern Hemisphere tropics (the physical explanation for these differences are discussed in Fasullo and Richter, 2022). Bednarz et al. (2022) also highlight that larger injection rates are needed in  $GLENS_{SAI}$  to reach the same amount of global cooling as in  $ARISE_{SAI}$  or to offset the end of the century RCP8.5 scenario.

All GCMs provide data with horizontal resolution of  $1.25^\circ$  longitude x  $0.9^\circ$  latitude. We highlight that one limitation of this study is the availability of projections with 6-hour frequency needed to track cyclones. When this study was started, the only available projections were the ones used here. Since the focus of this study is on extratropical cyclones, which are synoptic systems (horizontal dimension on the order of  $10^3$  km), the horizontal resolution of the datasets do not need to be high. Thus, all projections were interpolated to  $1.5^\circ$  longitude x  $1.5^\circ$  latitude using the bi-linear interpolation method (Wahab, 2017; Cerlini et al., 2020). The ensemble mean for each model will be used since each project has considerable differences. Hence, it can be expected that the different projects would lead to differences in the spatial pattern of the extratropical cyclones' characteristics.



**Table 1** Mean characteristics of the three projects. The used period in the study is indicated by \*. In the lines “Ensemble size” the numbers inside parentheses indicate the members available online. For instance, GLENS no-SAI has 17 members but only the realizations 001, 002 and 003 are available.

	ARISE	GLENS	GeoMIP/G6sulfur
Model version	CESM2(WACCM6)	CESM1(WACCM5)	MPI-ESM-LR
Main references	Richter et al. (2022) Hueholt et al. (2023)	Tilmes et al. (2018) Hueholt et al. (2023)	Wieners et al. (2019) Niemeier et al., (2019) Visioni et al. (2021)
Spatial resolution (longitude/latitude)	1.25°x0.9°	1.25°x0.9°	1.25°x0.9°
Calendar	365 d	365 d	365/366 d* *February 29 is removed
Ensemble size (no-SAI)	5 members 2015–2069* 5 members 2015–2100 (it does not have 6-hourly data)	17 members 2010–2030 (001-003) 3 members 2010–2097* (004-020)	3 members (r1i1p1f1, r2i1p1f1, r3i1p1f1) 2015-2100*
Ensemble size (SAI)	10 members 2035–2069*	20 members 2015–2099* (001-020)	3 members (r1i1p1f1, r2i1p1f1, r3i1p1f1) 2015-2100*
Forcing scenario	SSP2-4.5: Moderate mitigation	RCP8.5: No mitigation	SSP5-8.5: No mitigation
Global mean surface temperature target	2020–2039 average of first 5 SSP2-4.5 members ( $\approx 1.5^\circ\text{C}$ above pre-industrial)	2015–2024 average of first 13 RCP8.5 members ( $\approx 1.1^\circ\text{C}$ above pre-industrial)	reduce the globally averaged surface temperature down to the SSP2-4.5 level
SAI deployment year	2035	2020	2020
Injection height	$\approx 21$ km	$\approx 25$ km	between 18 and 20 km
Injection sites	30° and 15°N/S, all at 180°E	30° and 15°N/S, all at 180°E	continuous from 10° N - 10° S all at Greenwich meridian
Injection intensity rate	linear increase from 0.5 Tg-SO <sub>2</sub> per year	0.55 Tg-SO <sub>2</sub> per year	0.6 Tg-SO <sub>2</sub> per year
Injection amount	$\approx 10$ Tg-SO <sub>2</sub> /yr (2069)	$\approx 50$ Tg-SO <sub>2</sub> /yr (2099)	36 Tg-SO <sub>2</sub> /yr (2100)
Injection duration	2035–2069 (34 years)	2020–2099 (79 years)	2020-2100 (80 years)

## 2.2 Extratropical Cyclone Tracking

Cyclones were identified and tracked using 6-hourly MSLP data with an objective method (algorithm) developed by Murray and Simmonds (1991a,b) and updated by Simmonds and Murray (1999) and Simmonds et al. (1999). This algorithm has demonstrated reliable results in studies of extratropical cyclones over the Southern Hemisphere (Pezza and Ambrizzi, 2003; Neu et al., 2013; Reboita et al., 2015; Grieger et al., 2018).



Initially, the algorithm interpolates the MSLP from a regular (latitude-longitude) grid to a polar stereographic grid centered on the South Pole using the bicubic spline method, which eliminates anisotropy (it ensures that the grid resolution is uniform in all directions, mainly in the pole, Simmonds et al., 2003). Next, the Laplacian of pressure ( $\nabla^2 p$ ) for each grid point is calculated. Grid points candidate to be a cyclone are identified where there is a local maximum of  $\nabla^2 p$  (which is associated with the minimum pressure) compared to that of the surrounding eight grid points. This process is carried out for all timesteps, and only systems with  $\nabla^2 p$  exceeding  $0.2 \text{ hPa } (\text{lat})^{-2}$  are considered for the following analyses (Simmonds and Murray, 1999). Once the algorithm has identified the candidate grid points to be cyclones in all timesteps, it is necessary to connect these points over a sequence of timesteps to track the systems. This procedure comprises three stages (Simmonds et al., 1999): (a) predicting the subsequent position of each low-pressure center, (b) calculating the probability of an identification between the predicted cyclone and each cyclone identified at the new timestep (identified with  $\nabla^2 p$ ), and (c) defining the position of the minimum of pressure in the new timestep based on the highest probability of association obtained in stage (b). In summary, the tracking procedure is based on projecting cyclone positions from one analysis time to the next and comparing the projected positions with those of the cyclone analysis at the new time (Simmonds and Murray, 1999).

The algorithm provides, for each timestep of a cyclone's trajectory (latitude and longitude), the central pressure and  $\nabla^2 p$ . The  $\nabla^2 p$  (calculated between the center of the system and the neighborhood) can be taken as measure of the strength of the cyclone, and values greater than  $0.7 \text{ hPa } (\text{lat})^{-2}$  are classified as strong systems, while values between  $0.7$  and  $0.2 \text{ hPa } (\text{lat})^{-2}$  are considered weak (Simmonds and Murray, 1999). Knowing the cyclone trajectories, the algorithm is able to create a grid with some statistical quantities computed over different time scales (monthly, seasonal, yearly etc.) as specified by the user. These statistics are trajectory density (SD), central pressure (CP), radius (R0), and depth (DP) of cyclones. The SD corresponds to the normalized number of systems passing through a given area, which is calculated by summing contributions from all sampled positions (recorded along the tracks) and normalizing by an area of  $10^3 (\text{degrees latitude})^2$ . CP represents the minimum pressure at the center of the cyclones, R0 indicates the distance between the cyclone center and the location where  $\nabla^2 p = 0$ , and DP, is also a measure of cyclone strength. Although there is an expression to compute DP (see Simmonds et al., 2003), it can be understood as the MSLP difference between the center and the region of the system with  $\nabla^2 p = 0$  (cyclone external border); the values given by this variable are positive. Further details about these quantities are provided in Lim and Simmonds (2002). In this study, we computed the statistics on an annual basis.

### 2.3 Analyses

Extratropical cyclones were identified in each member of ARISE, GLENS, and GeoMIP/G6sulfur no-SAI and SAI projections. Climatologies were calculated using only cyclones with a lifetime equal to or greater than 24 hours, and presented in terms of ensemble mean. Cyclone frequency is defined as the number of systems per month, season (DJF, MAM, JJA and SON) and year.

Trends and their statistical significance ( $\alpha = 0.05$ ), using Sen's slope and Mann-Kendall test (Mann, 1945; Kendall, 1975), respectively, were calculated for the annual time series



(2015-2099) of cyclone frequency, initial pressure, minimum pressure along the lifecycle, lifetime, travelling distance, and mean velocity. The t-test at the 0.05 significance level (Wilks, 2020) was conducted to determine whether differences exist between the averages of the no-SAI and SAI scenarios at the same timeslice.

As shown in **Table 1**, not all projects have data before 2015. Hence, we considered the period 2015-2024 from no-SAI projections as the reference period. This allows us to analyze the difference between the future timeslices (2040-2059, and 2080-2099) and the current period (2015-2024). In addition, the differences between the no-SAI and SAI scenarios are analyzed for annual mean features of the cyclones and displayed in maps. In these maps, significance statistical tests for mean difference are not included due to the weakness of the tests for cyclone's properties on the grid, as these systems have high variability in space and time (Pezza et al., 2008, 2012; Catto et al., 2011; Reboita et al., 2015; Gentile et al., 2023).

### 3 Results and Discussions

#### 3.1 Trends

The annual frequency of extratropical cyclones over the Southern Hemisphere from 2015 to 2099 in each ensemble is depicted in **Figure 1a**. Additionally, to provide a view of the spread among the members of each project, the minimum and maximum annual frequency identified for no-SAI and SAI scenario members are shown. Up until 2050, the ensembles do not indicate a large difference in the annual frequency of cyclones between the no-SAI and SAI scenarios. However, from the 2050-decade, SAI scenarios indicate a higher number of systems (**Figure 1a**), contributing to a smoother negative trend, and even positive one in  $GLENS_{SAI}$ , when compared with that from no-SAI scenarios (**Table 2**). The negative trends under no-SAI scenarios are consistent with the findings in the literature (Bengtsson et al., 2009; Reboita et al., 2021a; de Jesus et al., 2021; Priestley and Catto 2022; Xu et al., 2023). **Table 2** reveals that, except for  $ARISE_{SAI}$  and  $GLENS_{SAI}$  projections, all the others exhibit statistically significant trends. In general, under the SAI scenarios, the frequency of extratropical cyclones is higher than under no-SAI scenarios and also higher than in the reference period (2015-2024), except in  $GeoMIP_{SAI}$  (**Table 3**). When the t-test is applied to identify whether the averages between the no-SAI and SAI scenarios at the same timeslice are statistically different, most timeslices and projects present statistically significant differences except for  $GeoMIP_{SSP5-8.5/SAI}$  in 2060-2069 and 2080-2089 (**Table 3**).

In future warming scenarios, the decrease in the frequency of extratropical cyclones is related to many interacting processes resulting in a complex picture. These include tropical upper-tropospheric warming (Kumar et al., 2022), which leads to an expansion of the Hadley cell and, consequently, a poleward expansion of the regions with higher MSLP and subtropical anticyclones (Reboita et al., 2019); polar near-surface warming, which leads to the weakening of the horizontal temperature gradients and, consequently, baroclinicity in mid-latitudes (Frederiksen et al., 2016) resulting in the poleward migration of the storm tracks; increasing the amplitude of large waves and decreasing the amplitude of short waves (synoptic waves; Schemm and Röthlisberger, 2024), further negatively affecting near-surface cyclogenesis. It is suggested that with the decrease in global warming caused by SAI, these processes will undergo fewer changes and consequently affect cyclones less. However,



additional investigation of the mechanisms is necessary and is beyond the scope of this study.

The trend of the annual mean of the central MSLP during cyclogenesis and the minimum pressure (cyclone deepest phase across) along its lifecycle are presented in **Figures 1b** and **1c**, respectively. In both figures, the no-SAI scenarios project a negative and statistically significant trend (**Table 2**), indicating that cyclones will be deeper in the future since lower central pressure is the main indicator of more intense cyclones. For instance, GeoMIP<sub>SSP5-8.5</sub> scenario indicates that the cyclones at the end of the century will be 3.1 and 4 hPa stronger for initial pressure (**Table 4**) and minimum pressure (**Table 5**), respectively, than in the present climate. Under SAI scenarios, the ARISE<sub>SAI</sub> and GLENS<sub>SAI</sub> project a positive trend in MSLP (**Figure 1b-c**), corresponding to weaker systems in the future (**Table 2**). Only GeoMIP<sub>SAI</sub> projects a negative trend, but it has a smoother slope compared to the no-SAI scenario (**Table 2**). **Tables 4** and **5** also indicate that in all timeslices cyclones are weaker under the SAI compared to no-SAI scenarios (in other words, MSLP is higher in SAI scenarios) and the differences are statistically significant. This is also observed when comparing the timeslices of SAI scenarios with the reference period; only GLENS<sub>SAI</sub> projects systems slightly deeper than in the reference period.

It appears controversial that with a decrease in baroclinicity in warming scenarios, extratropical cyclones can exhibit greater intensity. However, as shown in the literature, this is a consequence of higher moisture availability contributing to diabatic processes in the cyclone's environment (Kodama et al., 2019; Catto et al., 2019; Sinclair et al., 2020; Reboita et al., 2021b).

While there is a clear signal regarding future trends for the aforementioned variables, there are more uncertainties concerning traveling distance. While ARISE<sub>SSP2-4.5</sub> and GLENS<sub>RCP8.5</sub> scenarios project a negative trend for the travelling distance, GeoMIP<sub>SSP5-8.5</sub> projects a positive one. On the other hand, ARISE<sub>SAI</sub> and GeoMIP<sub>SAI</sub> have opposite trends compared with no-SAI scenarios, and GLENS<sub>SAI</sub> projects a more intense negative trend than under no-SAI. Only ARISE<sub>SSP2-4.5/SAI</sub> does not have a statistically significant trend (**Table 2**). As shown in **Table 6**, cyclone's travel distances range between 3000 and 3300 km, indicating a small mean difference of only 300 km (10%) in the trajectory of the cyclones. Nevertheless, the differences are statistically significant, except in 2060-2069 for ARISE<sub>SSP2-4.5/SAI</sub> and in 2070-2079 for GeoMIP<sub>SSP8-8.5/SAI</sub> (**Table 6**).

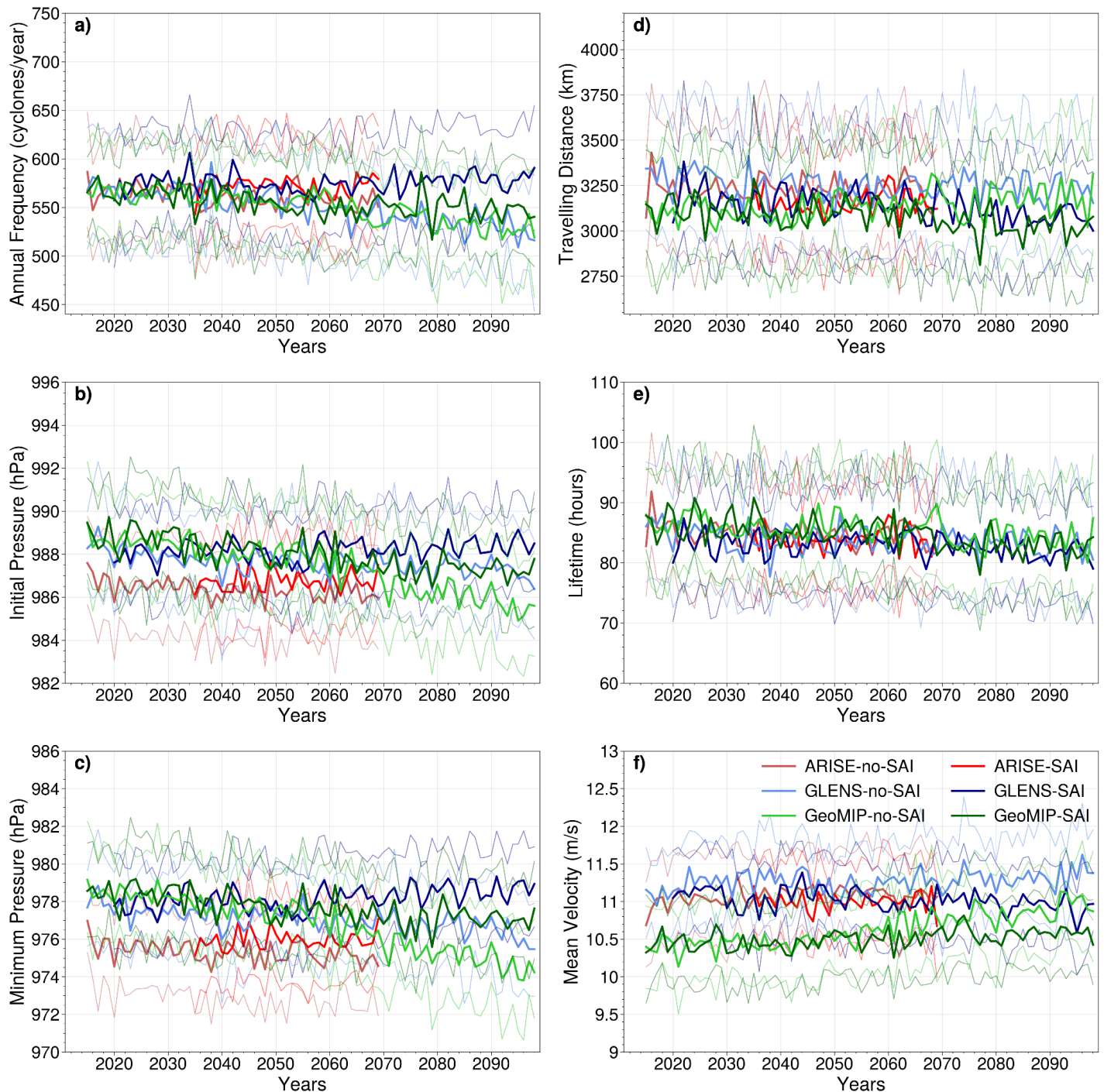
Extratropical cyclones exhibit a negative trend in their lifetime, but that does not exceed ~4 hours (4% of their total duration) between the reference period and the end of the century in both no-SAI and SAI scenarios (**Figure 1e**). Despite this small value, the trends are statistically significant, except for the ARISE<sub>SSP2-4.5/SAI</sub> scenarios (**Table 2**). Under SAI scenarios although cyclones are less deep (**Table 5**) their duration seems not to be affected (**Table 7**).

As mean velocity is a relation between traveling distance and lifetime, the small changes projected for both variables throughout the future (**Tables 6** and **7**) result in small changes in mean velocity (**Figure 1f** and **Table 8**). The maximum difference between SAI and no-SAI scenarios is 0.5 m s<sup>-1</sup> in GLENS<sub>RCP8.5/SAI</sub> in 2090-2099 (**Table 8**), which implies slower cyclones under SAI scenario. Although trends are not visually apparent in **Figure 1f**, the



calculated trend slope reveals a positive and statistically significant trend for all datasets except for the  $ARISE_{SAI}$ , which shows no trend, and the  $GLENS_{SAI}$ , which exhibits a negative and significant trend (**Table 2**). In **Table 8**, the t-test for average differences between the scenarios only indicated no significance for  $ARISE_{SSP2-4.5/SAI}$ .

Overall, the slight changes projected for travelling distance, lifecycle, and mean velocity until the end of the century under no-SAI scenarios are consistent with findings from studies, such as Reboita et al. (2021b) and Sinclair et al. (2020).



**Figure 1** Extratropical cyclone trends over the Southern Hemisphere under no-SAI and SAI scenarios from 2015 to 2099: a) annual frequency (number per year), b) initial pressure (registered in the cyclogenesis, hPa), c) minimum pressure during the whole lifecycle (hPa), d) travelling distance (km), e) lifetime (hours), and f) mean velocity ( $\text{m s}^{-1}$ ). Bold lines indicate the ensemble mean and light lines indicate the minimum and maximum values obtained by the members of each ensemble.



**Table 2** Slope of the trends calculated for the annual time series (slope year<sup>-1</sup>) of each ensemble shown in **Figure 1**. Trends statistically significant at the level of  $\alpha = 0.05$  are highlighted in bold.

Project	Annual Frequency	Initial Pressure	Minimum Pressure	Travelling Distance	Lifetime	Mean Velocity
ARISE <sub>SSP2-4.5</sub>	<b>-0.282</b>	<b>-0.011</b>	<b>-0.014</b>	-0.301	-0.022	<b>0.002</b>
ARISE <sub>SAI</sub>	-0.016	0.004	0.008	0.600	0.034	0.000
GLENS <sub>RCP8.5</sub>	<b>-0.563</b>	<b>-0.012</b>	<b>-0.018</b>	<b>-0.816</b>	<b>-0.028</b>	<b>0.002</b>
GLENS <sub>SAI</sub>	0.102	<b>0.005</b>	<b>0.012</b>	<b>-1.651</b>	<b>-0.027</b>	<b>-0.002</b>
GeoMIP <sub>SSP5-8.5</sub>	<b>-0.548</b>	<b>-0.042</b>	<b>-0.054</b>	<b>1.353</b>	<b>-0.038</b>	<b>0.008</b>
GeoMIP <sub>SAI</sub>	<b>-0.286</b>	<b>-0.024</b>	<b>-0.021</b>	<b>-1.421</b>	<b>-0.057</b>	<b>0.002</b>

**Table 3** Mean annual frequency of extratropical cyclones over the Southern Hemisphere obtained by the ensemble of no-SAI and SAI scenarios from ARISE-SAI, GLENS and GeoMIP for different timeslices. The asterisk (\*) indicates that the difference between no-SAI and SAI averages in the same timeslice is statistically significant at the level of 0.05.

Project	2015-2024	2060-2069	2070-2079	2080-2089	2090-2099
ARISE <sub>SSP2-4.5</sub>	565.3	554.8	-	-	-
ARISE <sub>SAI</sub>	-	573.0 *	-	-	-
GLENS <sub>RCP8.5</sub>	566.5	544.9	537.4	534.4	525.5
GLENS <sub>SAI</sub>	-	574.1 *	576.9 *	580.2 *	578.7 *
GeoMIP <sub>SSP5-8.5</sub>	565.1	543.2	543.7	531.2	528.9
GeoMIP <sub>SAI</sub>	-	548.8	548.5	550.5 *	545.5 *

**Table 4** Similar to **Table 3** but for initial pressure (hPa).

	Project	2015-2024	2060-2069	2070-2079	2080-2089	2090-2099
Initial Pressure (hPa)	ARISE <sub>SSP2-4.5</sub>	986.6	986.2	-	-	-
	ARISE <sub>SAI</sub>	-	986.8 *	-	-	-
	GLENS <sub>RCP8.5</sub>	988.2	987.6	987.4	987.5	987.0
	GLENS <sub>SAI</sub>	-	988.3 *	988.3 *	988.4 *	988.5 *
	GeoMIP <sub>SSP5-8.5</sub>	988.6	987.4	986.2	986.1	985.5
	GeoMIP <sub>SAI</sub>	-	987.7	987.2 *	987.4 *	987.3 *

**Table 5** Similar to **Table 3** but for minimum pressure along the cyclone's lifetime (hPa).

	Project	2015-2024	2060-2069	2070-2079	2080-2089	2090-2099
Minimum Pressure (hPa)	ARISE <sub>SSP2-4.5</sub>	975.6	975.0	-	-	-
	ARISE <sub>SAI</sub>	-	976.0 *	-	-	-
	GLENS <sub>RCP8.5</sub>	977.8	977.0	976.7	976.8	976.0
	GLENS <sub>SAI</sub>	-	978.3 *	978.5 *	978.6 *	978.7 *
	GeoMIP <sub>SSP5-8.5</sub>	978.4	976.6	975.4	975.1	974.4
	GeoMIP <sub>SAI</sub>	-	977.5 *	976.9 *	977.3 *	977.0 *

**Table 6** Similar to **Table 3** but for travelling distance (km).

	Project	2015-2024	2060-2069	2070-2079	2080-2089	2090-2099
Travelling Distance (km)	ARISE <sub>SSP2-4.5</sub>	3251.5	3222.3	-	-	-
	ARISE <sub>SAI</sub>	-	3161.7	-	-	-
	GLENS <sub>RCP8.5</sub>	3305.7	3232.5	3262.2	3230.9	3237.9
	GLENS <sub>SAI</sub>	-	3144.4 *	3118.3 *	3063.6 *	3082.7 *
	GeoMIP <sub>SSP5-8.5</sub>	3113.1	3190.5	3118.9	3194.9	3185.9
	GeoMIP <sub>SAI</sub>	-	3083.6 *	3032.4	3012.7 *	3035.1 *

**Table 7** Similar to **Table 3** but for cyclone's lifetime (hours).

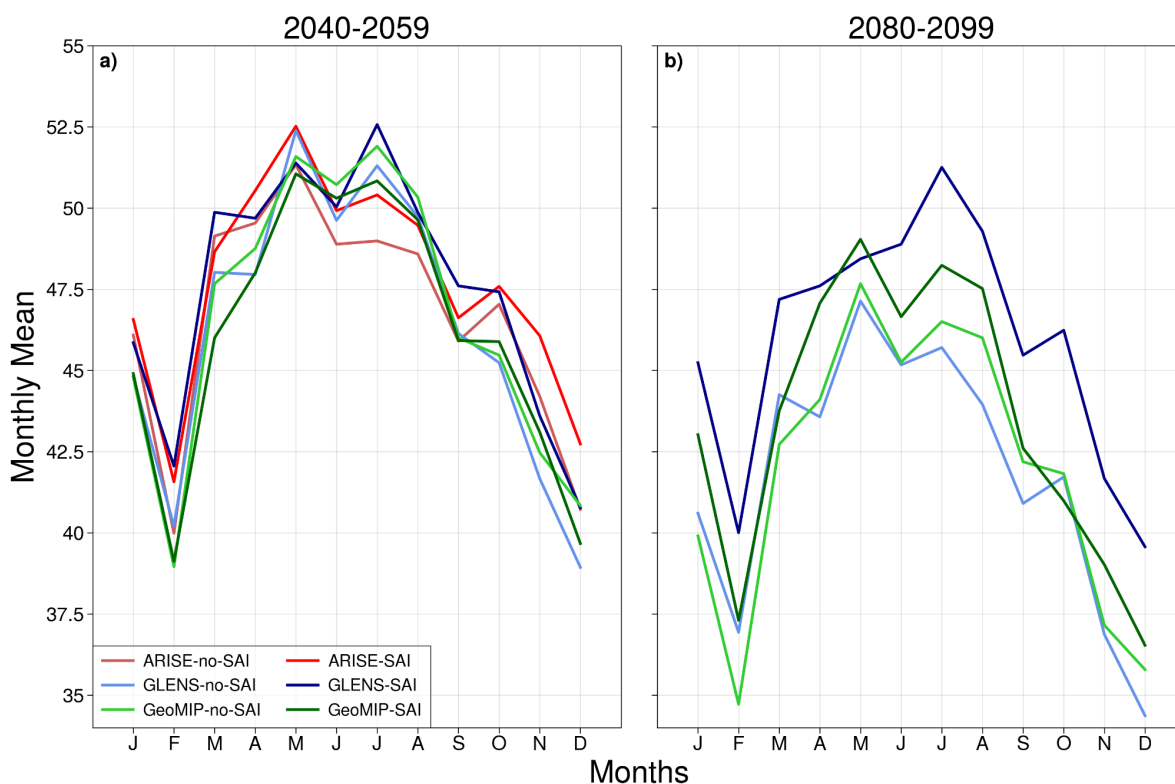
	Project	2015-2024	2060-2069	2070-2079	2080-2089	2090-2099
Lifetime (h)	ARISE <sub>SSP2-4.5</sub>	86.0	84.7	-	-	-
	ARISE <sub>SAI</sub>	-	83.9	-	-	-
	GLENS <sub>RCP8.5</sub>	85.8	83.2	83.6	83.2	82.9
	GLENS <sub>SAI</sub>	-	83.2	82.6	81.6	81.8
	GeoMIP <sub>SSP5-8.5</sub>	86.8	86.4	83.1	84.6	83.7
	GeoMIP <sub>SAI</sub>	-	85.2	82.8	82.7	82.7

**Table 8** Similar to **Table 3** but for mean velocity ( $\text{m s}^{-1}$ ).

	Project	2015-2024	2060-2069	2070-2079	2080-2089	2090-2099
Mean Velocity (m/s)	ARISE <sub>SSP2-4.5</sub>	11.0	11.0	-	-	-
	ARISE <sub>SAI</sub>	-	11.0	-	-	-
	GLENS <sub>RCP8.5</sub>	11.1	11.3	11.3	11.3	11.4
	GLENS <sub>SAI</sub>	-	11.0 *	11.0 *	11.0 *	10.9 *
	GeoMIP <sub>SSP5-8.5</sub>	10.4	10.7	10.8	10.8	11.0
	GeoMIP <sub>SAI</sub>	-	10.5 *	10.6 *	10.6 *	10.6 *

### 3.2 Annual Cycle

The annual cycle of extratropical cyclones in both scenarios considering two periods (2040-2059 and 2080-2099) is shown in **Figure 2**. There is a high frequency of cyclones between May and August, which is the period with higher baroclinicity in the Southern Hemisphere (Holton, 2004; Frederiksen et al., 2016) and an important cyclogenesis driver. In December, the frequency of cyclones reaches a minimum, which is followed by another in February. When the ratio of cyclones per day for each month is computed the minimum in February is smoothed (Figure not shown). Therefore, the decrease in the cyclone frequency from January to February is due to February having fewer days (28 or 29), which affects the count of systems. These results are consistent with climatologies obtained for present and future climates (Hoskins and Hodges, 2005; Reboita et al., 2015; Marraffon et al., 2021, 2022). Some of the results from **Figure 1** are also evident in **Figure 2**: a decrease in the frequency of cyclones towards the end of the century, but with a weaker decrease under SAI scenarios (**Figure 2b**).



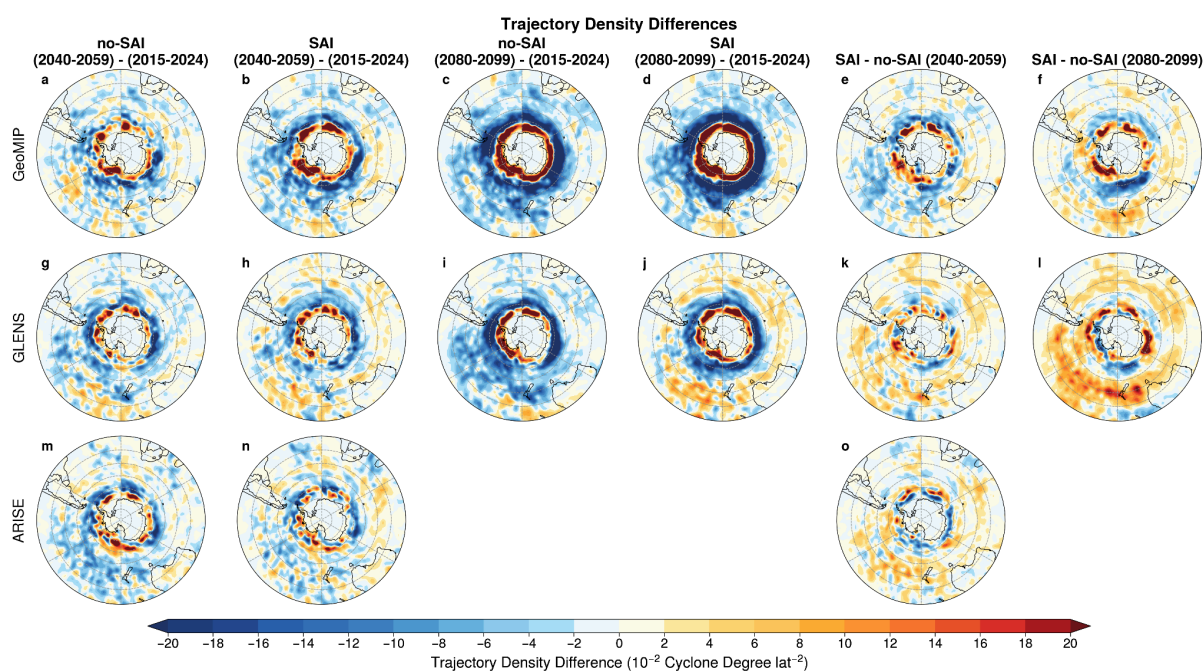
**Figure 2** Annual cycle of the frequency of extratropical cyclones under no-SAI and SAI scenarios considering a) 2040-2059 and b) 2080-2099 periods.

### 3.3 Spatial Pattern

In this section, the spatial pattern of extratropical cyclones characteristics (**Figure 3-6**) is presented in terms of comparisons between the future and the reference period, as well as between no-SAI and SAI scenarios.

The future timeslices under no-SAI scenarios indicate a decrease in the SD frequency, mainly in mid-latitudes, and an increase around Antarctica compared to the reference period (**Figure 3a,c,g,i,m**), which is known in the literature as the poleward shift of the storm tracks under global warming scenarios (Mbengue and Schneider, 2013; Chemke, 2022). In GeoMIP<sub>SSP5-8.5</sub> (**Figure 3a,c**) the decrease is more pronounced than in the other datasets near the continents (southeastern South America, and Southern Africa and Australia). These patterns become stronger towards the end of the century (**Figure 3c**). SAI scenarios also project a decrease in SD compared to the reference period, but this decrease is lower than that observed under no-SAI scenarios (**Figure 3b,d,h,j,n**), which compensates for the effect of global warming. This is clearer in the difference between SAI and no-SAI scenarios, where positive differences (indicative of higher SD under SAI scenarios) predominate mainly around Antarctica and in the latitudes of eastern Australia (**Figure 3e,f,k,l,o**). GLENS<sub>SAI</sub> shows an increase in the SD over the South Pacific compared to the reference period (**Figure 3h,j**). This signal is weak in GeoMIP<sub>SAI</sub> and only appears in eastern Australia. Hence, the positive SD in GLENS is in general opposite between SAI no-SAI scenarios, therefore affecting patterns of the other analyzed variables. This different signal in GLENS<sub>SAI</sub> might be related

with the spreading of aerosols in this projection, which has largest concentrations of sulfate in the tropical band of the Northern Hemisphere (Richter et al., 2022), and their response to the atmospheric circulation. In this SAI scenario, Bednarz et al. (2022) found a strengthening of the stratospheric zonal winds that extends downwards to the troposphere, resulting in a poleward shift of the eddy-driven jet and sea-level pressure anomalies, corresponding to the positive phase of the Southern Annular Mode (SAM). According to Reboita et al. (2015), SAM positive phase is related with a tri-pole in the spatial distribution of cyclones: higher frequency near Antarctica and northward 45°S and lower frequency between these two bands. On the other hand, Bednarz et al. (2022) also indicated an opposite response in ARISE<sub>SAI</sub> (which has largest concentration of aerosol in the tropics of the Southern Hemisphere), that is, an equatorward shift of the eddy-driven jet and a sea-level pressure response resembling a negative phase of SAM that can difficult the occurrence of cyclones northward 45°S (Reboita et al., 2015).



**Figure 3** Cyclone tracking density (SD) projections for each project (GeoMIP/G6sulfur, GLENS and ARISE). The first to fourth columns indicate the difference between different timeslices and the reference period for a,c,g,i,m) no-SAI and b,d,h,j,n) SAI scenarios, and the fifth and sixth columns indicate the difference between SAI and no-SAI scenarios.

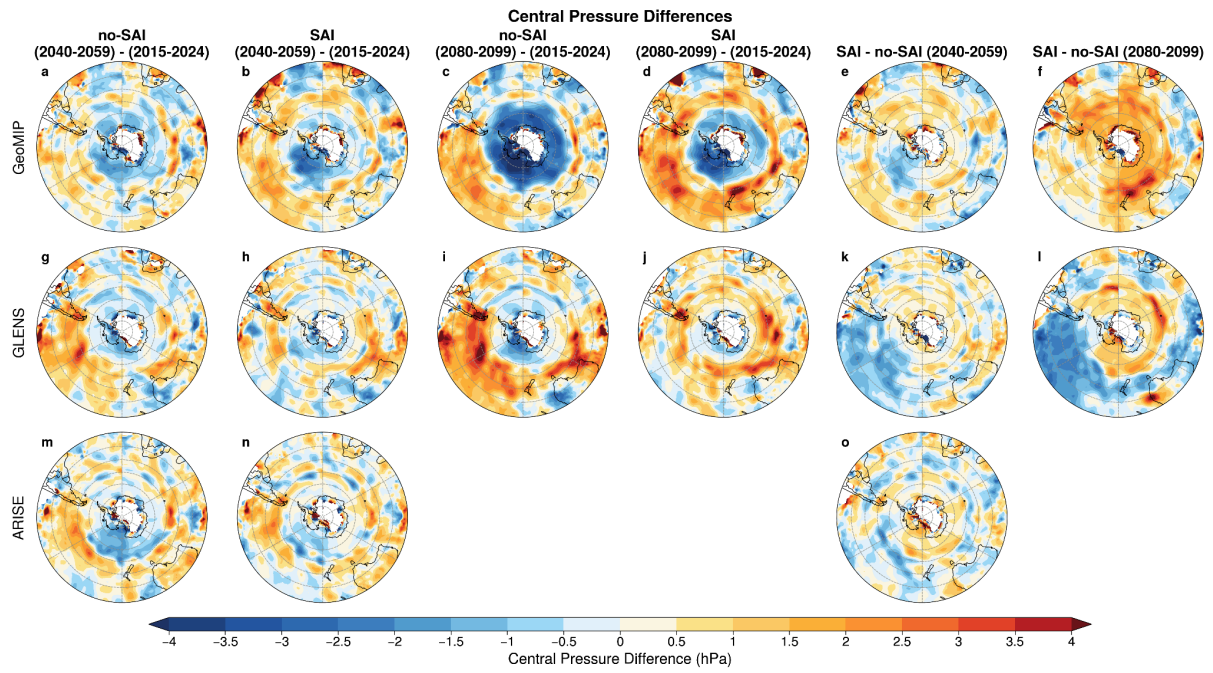
**Figure 1c** showed a general view of the MSLP trends in the cyclone's center in the Southern Hemisphere, but in a spatial analysis not the whole hemisphere may present the same CP trend signal. Indeed, both no-SAI (**Figure 4a,c,g,i,m**) and SAI (**Figure 4b,d,h,j,n**) scenarios project stronger systems southern 50°S, i.e., towards Antarctica (negative difference in the figures), and weaker in mid-latitudes and near the continental coasts (positive difference). However, there is a difference in SAI compared to no-SAI scenarios: while the increase in intensity of the systems (negative difference) is lower under SAI than under no-SAI scenarios, the decrease in the intensity (positive difference), in general, is higher. This means that, on average, SAI scenarios project weaker systems. Of course there are differences among the projects. For instance, GLENS<sub>SAI</sub> projects lower MSLP over the Pacific Ocean



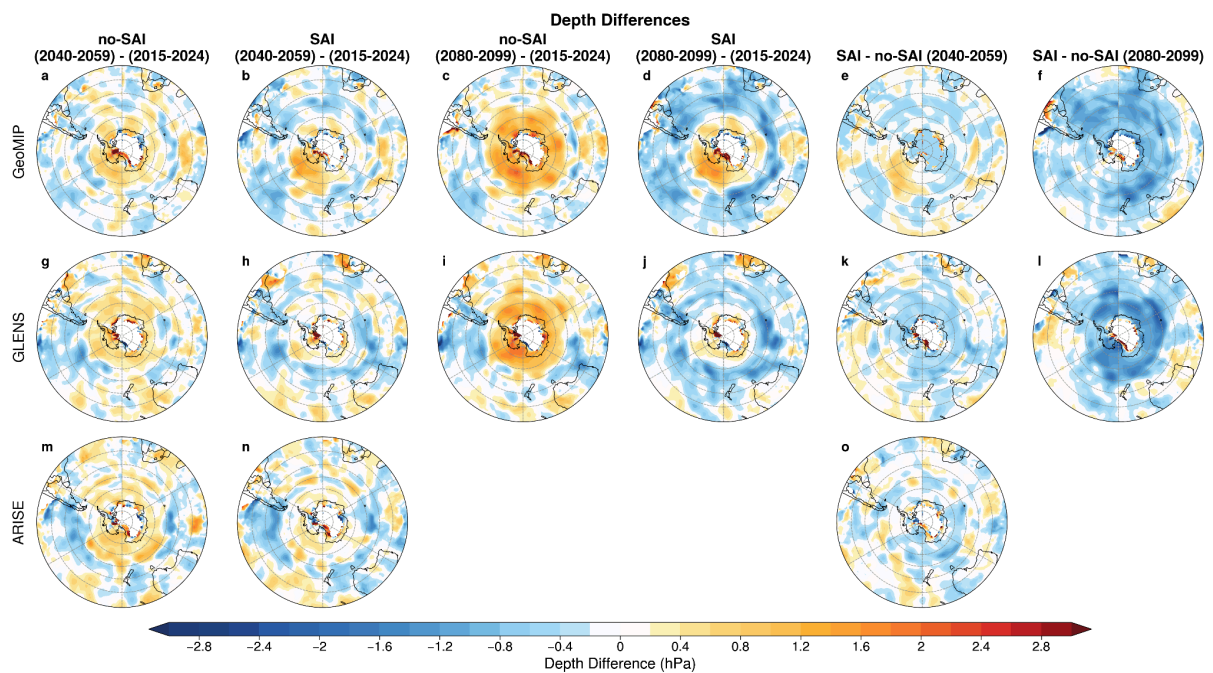
than  $\text{GLENS}_{\text{RCP8.5I}}$ , and also in comparison with  $\text{GeoMIP}_{\text{SSP5-8.5/SAI}}$ . This is a consequence of higher frequency of cyclones projected by  $\text{GLENS}_{\text{RCP8.5SAI}}$  over this ocean, which impacts the MSLP (**Figure 4e,f,k,l,o**).

As cyclones are perturbations superimposed on a background of the global pressure field, which is characterized by a MSLP decrease from lower to higher latitudes (Sinclair, 1994), it is expected cyclones with higher CP (weaker systems) in lower latitudes than in higher latitudes. Due to this fact, the real intensity of the cyclone can be masked when CP is analyzed. A more realistic measure of cyclone intensity is obtained through DP. It should be noted that weaker (stronger) cyclones have lower (higher) DP values; therefore, the DP differences in **Figure 5** will have opposite signals to CP in **Figure 4**. Despite the previous consideration, when comparing both variables under no-SAI and SAI scenarios, we find good agreement between the spatial distribution of regions with more intense systems and weaker ones. But, a difference occurs between DP and CP over the South Pacific: the CP field shows a larger area with weaker cyclones than DP (for instance in **Figure 5a,c,g,i,m**). This may be related to the fact that the global pattern of pressure is projected to change in the future, as indicated by various studies suggesting a polar amplification of the Hadley cell, leading to higher pressures towards mid-latitudes (Reboita et al., 2019 and their references). So, this background is being added to the cyclones environment leading to systems with higher MSLP values. However, in terms of real intensity, there are no great changes in DP over the South Pacific. In a nutshell, the DP confirms that in both future timeslices, under SAI scenarios, extratropical cyclones can be weaker under SAI than no-SAI scenarios (**Figure 5e,f,k,l,o**).

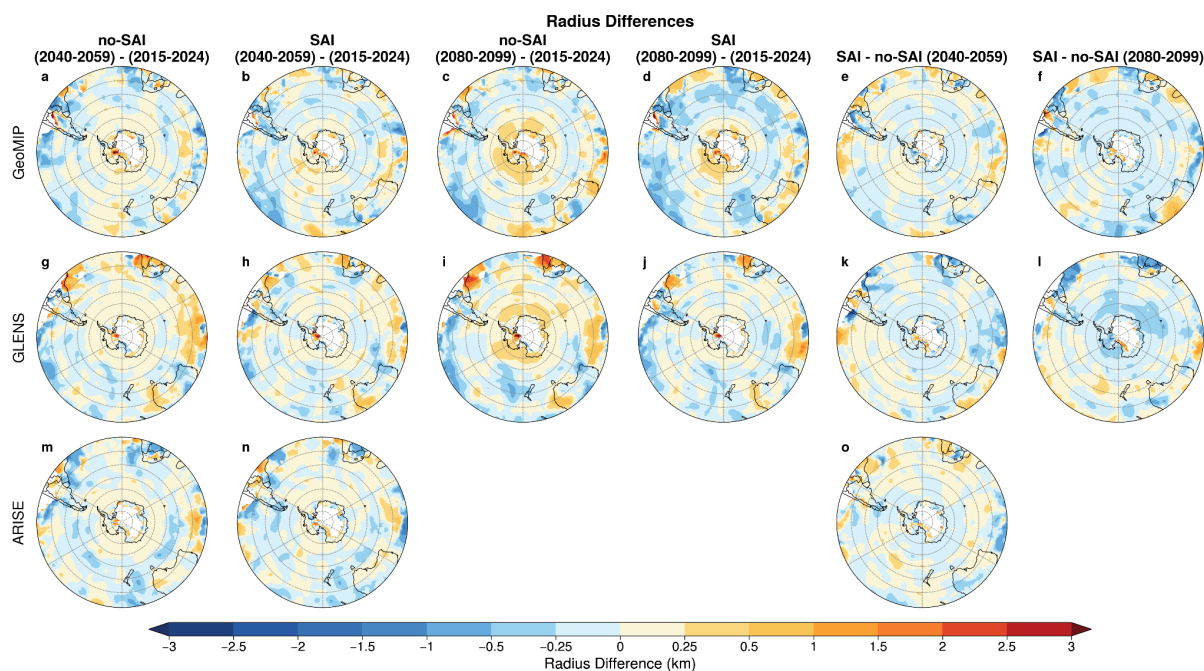
No-SAI and SAI scenarios practically do not indicate great changes in the R0 in the areas with an increase in DP near Antarctica, but project a decrease in mid-to-low latitudes for the period 2040-2059 (**Figure 6**). A signal of increasing R0 towards Antarctica and near the continents, mainly in southeastern South America, is projected for the period 2080-2099, meaning slightly bigger cyclones in future. In general, SAI scenarios project cyclones with slightly lower R0 than the no-SAI scenarios (**Figure 6e,f,k,l,o**).



**Figure 4** Similar to **Figure 3** but for cyclone central pressure (CP in hPa).



**Figure 5** Similar to **Figure 3** but for cyclone depth (DP in hPa).



**Figure 6** Similar to **Figure 3** but for cyclone radius ( $R_0$  in km).

#### 4. Conclusions

This study compared the impact of global warming in scenarios with (SAI) and without (no-SAI) stratospheric aerosol injection (SAI) on extratropical cyclone characteristics over the Southern Hemisphere using projections from three projects: ARISE, GLENS, and GeoMIP/G6sulfur. Despite differences in the projection configuration of the three projects, both no-SAI and SAI scenarios indicate trends in cyclone climatology in the same direction, giving confidence to the results. The main features in the extratropical cyclone climatology are summarized as follows:

*Frequency and annual cycle:* both no-SAI and SAI scenarios for present and future climate exhibit an annual cycle of extratropical cyclone frequency in phase with that described in the literature, with winter being the most cyclogenetic season. The frequency of cyclones decreases towards the end of the century, but with a weaker decrease under SAI scenarios. Therefore, SAI scenarios compensate for the lower frequency of cyclones in the global warming scenario (no-SAI).

*Intensity:* the intensity of extratropical cyclones under no-SAI and SAI scenarios obtained from different approaches (initial pressure, minimum pressure during the lifecycle, and depth) indicates that cyclones will be stronger at the end of the century. However, under SAI scenarios cyclones are less intense compared with no-SAI, highlighting that under SAI cyclones have more similar intensity to the reference period.

*Traveling distance, lifecycle and mean velocity:* there are small differences between the reference period and the end of the century under both no-SAI and SAI scenarios. In addition, the differences between these scenarios are also minimal in the whole studied period.



*Spatial patterns:* although the three projects (ARISE-SAI, GLENS, and GeoMIP/G6sulfur) under both no-SAI and SAI scenarios have some differences in the spatial patterns of cyclone features (trajectory density, central pressure, depth, and radius), they agree that the extratropical cyclones are decreasing (increasing) in density and intensity in mid-latitudes (towards Antarctica), which is a poleward shift of the storm tracks. In addition, they show that the radius of the cyclones can be smaller mainly in mid-to-low latitudes and bigger around Antarctica.

As this is the first study to address SAI in cyclones' climatology - from the tracking perspective - there are no other studies for comparison. However, all described features concerning the no-SAI are consistent with the literature (as shown by the references throughout the text) and they bring important information to the decision makers since coastal areas, such as southeastern South America and New Zealand, are vulnerable to more intense systems in the next decades (e.g. floods, heavy rains etc.). In addition, there is a consistent indication that the cyclone's climatology is less affected by global warming when SAI is considered.

In a subsequent study, we will evaluate cyclone synoptic patterns through composite analysis to elucidate the physical differences of these systems between no-SAI and SAI scenarios, which provide valuable insights in understanding the impacts of SAI on extratropical cyclones: vital systems to the thermal equilibrium of the planet.

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**Declaration:** The authors declare no conflict of interest.

**Data availability statement:** All datasets used in this study are available online at the links:

ARISE

[https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm2.waccm6.ssp245.atm.proc.3hourly\\_ave.html](https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm2.waccm6.ssp245.atm.proc.3hourly_ave.html)

ARISE-SAI

[https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm4.ARISE-SAI-1.5.atm.proc.3hourly\\_ave.html](https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm4.ARISE-SAI-1.5.atm.proc.3hourly_ave.html)

GLENS

[https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm4.GLENS.Control.atm.proc.6hourly\\_ave.html](https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm4.GLENS.Control.atm.proc.6hourly_ave.html)

GLENS-SAI [https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm4.GLENS.Feedback.atm.proc.6hourly\\_ave.html](https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm4.GLENS.Feedback.atm.proc.6hourly_ave.html)

GeoMIP



<https://esgf-node.llnl.gov/search/cmip6/>

G6sulfur

<https://view.es-doc.org/?renderMethod=name&project=cmip6&type=cim.2.designing.NumericalExperiment&client=esdoc-url-rewrite&name=g6sulfur>

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## 7. IMPACTS OF STRATOSPHERIC AEROSOL INJECTION ON PRECIPITATION AND WINDS ASSOCIATED WITH EXTRATROPICAL CYCLONES IN THE SOUTHERN HEMISPHERE

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## Impacts of stratospheric aerosol injection on precipitation and winds associated with extratropical cyclones in the Southern Hemisphere

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### Abstract

This study seeks to describe the impact of Stratospheric Aerosol Injection (SAI) under climate change scenarios on precipitation and 10-meter winds caused by extratropical cyclones in the Southern Hemisphere, using data from three international initiatives: the Earth System with Stratospheric Aerosol Injection (ARISE), the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS), and the Geoengineering Model Intercomparison Project (GeoMIP/G6Sulfur). Cyclone-related variables were examined across three time periods - the reference period (2015–2024), the near future (2040–2059), and the far future (2080–2099) - with a focus on four key subdomains: the Southeast Pacific Ocean (SPO), Southwest Atlantic Ocean (SAO), Southern Africa (AFR), and Australia (AUS). In the first part of the study, we assessed precipitation and wind intensity associated with cyclones under both SAI and no-SAI scenarios. Results show that the SAI scenario generally leads to cyclones with reduced precipitation and weaker winds compared to the no-SAI scenario, though exceptions were noted in the GeoMIP/G6Sulfur simulations. In the second part, we analyzed the contribution of extratropical cyclones to total precipitation and wind intensity within each subdomain. The findings reveal that this contribution decreases under the SAI scenario from the near to the far future. This trend is consistent across both precipitation and wind intensity. In the final part of the study, we examined the synoptic characteristics of extratropical cyclones in each subdomain using composite analysis. During the reference period, the three initiatives successfully reproduced the typical structure of extratropical cyclones as observed in reanalysis data, albeit with differences in the magnitude of precipitation. In contrast, there is no spatial homogeneity in the composite differences between SAI and no-SAI during the future periods. For example, one project may show reduced precipitation in a specific quadrant of the cyclone in one domain, but display a different pattern in others. This variability is also observed across different projects and time periods analyzed. The main conclusion is that SAI appears to mitigate some of the effects of global warming by weakening extratropical cyclones, and contributing to decreasing regionally precipitation and wind intensity associated with these systems.

**Keywords:** climate change, extratropical cyclones, Southern Hemisphere, climate intervention, precipitation, 10-m wind intensity



## 1. Introduction

The year 2024 marked the first time in recorded history that global mean temperature anomalies exceeded 1.5 °C (reaching 1.6 °C) above the 1850-1900 pre-industrial level (Copernicus 2025). The Paris Agreement (UNFCCC 2015), noted that if global temperature rises surpass 2 °C, the planet will face the consequences linked to tipping points - irreversible processes (McKay et al 2022), for example severe mass loss from the west Antarctic and Greenland ice sheets, which are essentially irreversible. Faced with this urgent challenge, many consider it imperative to develop strategies to mitigate environmental degradation and safeguard the systems that support human life.

Even cutting all global emissions to zero, the planet will take years to cool down. In this context, the United Nations Environment Programme (UNEP 2023) declared that “*Solar Radiation Modification (SRM) is the only option that could cool the planet within years*”. SRM aims to cool the Earth by reflecting a small percentage of sunlight back into space. This strategy is a category of solar geoengineering, which is also known as solar climate engineering or solar climate intervention. Stratospheric Aerosol Injection (SAI) is the most studied SRM method and involves injecting aerosols (usually sulfur) into the stratosphere to reflect sunlight and cool the Earth's surface. While essentially all SRM studies suggest benefits compared with climate impacts from greenhouse gas forced temperature rises, any implementation would require far more extensive studies to evaluate its impacts on various components of the climate system.

To advance understanding in this field, the Degrees Initiative, a non-governmental organization, has been encouraging and funding research to improve knowledge of SRM, stating that “*The use or rejection of SRM could be one of the biggest decisions humanity has faced, and this matters most to climate-vulnerable regions.*” (<https://www.degrees.ngo/>). Most of the studies in this context have focused on changes in climate variables such as air temperature and precipitation and their extreme events across the globe (Bonou et al 2023, Patel et al 2023, Tew et al 2023, Narenpitak et al 2024, Xavier et al 2024, Hussain et al 2025). On the other hand, few studies have addressed the impact of SAI on atmospheric systems that lead to extreme events in the Southern Hemisphere. This is particularly true for atmospheric systems in the Southern Hemisphere. Baldoni et al. (2025) evaluated the influence of SAI on the South Atlantic Subtropical Anticyclone (SASA), which is an important atmospheric system responsible for organizing precipitation or disfavoring it around South America. These authors, like others, utilized SAI climate projections from three international initiatives: Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection (ARISE), the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS), and the Geoengineering Model Intercomparison Project (GeoMIP/G6Sulfur), each with distinct experimental designs. Baldoni et al. (2025) found that under greenhouse-gas forcing alone—that is, in future scenarios without SAI—the SASA becomes stronger and wider compared to both the reference period and scenarios with SAI.

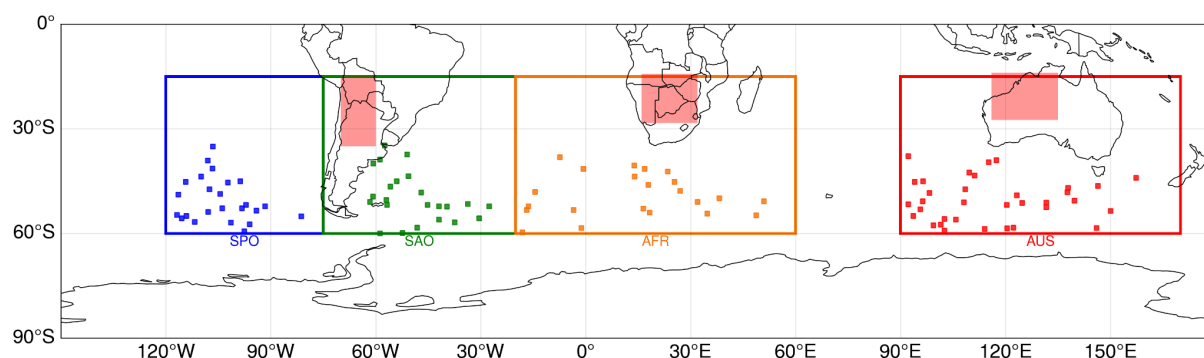
Reboita et al (2024a) used the same projections as Baldoni et al (2025) to evaluate the influence of SAI on the climatology of extratropical cyclones over the Southern Hemisphere. Their key findings indicate that while both SAI and no-SAI scenarios project a decrease in cyclone frequency toward the end of the century, the reduction is less pronounced under SAI

scenarios. Additionally, cyclones are projected to be more intense under no-SAI scenarios, whereas their intensity remains closer to the reference period under SAI scenarios. In a nutshell, this study demonstrated that SAI scenarios bring the extratropical cyclone climatology closer to that of the reference period. To further explore characteristics associated with these systems, we investigate other aspects of extratropical cyclones over the Southern Hemisphere, particularly wind and precipitation, under both SAI and no-SAI scenarios in ARISE, GLENS and GeoMIP/G6Sulfur initiative.

## 2. Methodology

### 2.1. Study Area

The study area covers the Southern Hemisphere, between latitudes 20°S and 60°S. For more detailed analyses, four subdomains are defined (**Figure 1**): southeastern South Pacific Ocean (SPO), southwestern South Atlantic Ocean (SAO), which takes into account part of South America, south of Africa and its surrounding oceans (AFR), and Australia and its surrounding oceans (AUS). These regions were selected due to the specificities of cyclone's drivers in each subdomain (Reboita et al 2021a,b).



**Figure 1** Subdomains used in the study: southeastern South Pacific Ocean (SPO; blue box), southwestern South Atlantic Ocean (SAO; green box), south of Africa and its surrounding oceans (AFR; orange box), Australia and its surrounding oceans (AUS; red box). Dots indicate the position of the 30th percentile of most intense cyclones when they reach the minimum mean sea level pressure within the subdomain during austral winter from 2015 to 2024 in ERA5 reanalysis. The shaded red rectangles indicate thermal low regions; systems originating from these areas are excluded from the analysis.

### 2.2. Projections and Data

Mean sea level pressure (MSLP), precipitation, and horizontal wind components at 10-m recorded every 6 hours (0000, 0600, 1200 and 1800 UTC) from three members of ARISE (Richter et al 2022), GLENS (Tilmes et al 2018), and GeoMIP/G6Sulfur (Vioni et al 2021, Kravitz et al 2015, Vioni et al 2023) initiatives, with and without SAI, are the variables used in this study. The primary differences among these initiatives lie in the atmospheric models used and the global warming scenarios considered. GLENS employs the NCAR Community Earth System Model version 1 (CESM1) with the Whole Atmosphere Community Climate



Model version 5 (WACCM5) as its atmospheric component, and projections are under RCP8.5. ARISE uses CESM2, coupled with the WACCM6, under the SSP2-4.5 scenario. GeoMIP/G6Sulfur has been performed by several different global climate models; however, for this study, the availability of 6-hour resolution data (Reboita et al. 2024a) drove the choice of the Max Planck Institute Earth System Model (MPI-ESM1-2-LR), with greenhouse gases from the SSP5-8.5 scenario.

In addition to differences in SAI initiation year (2020 in GLENS and GeoMIP/G6Sulfur and 2035 in ARISE), and different durations, another key distinction among these initiatives is the location of SAI implementation. In ARISE and GLENS, SO<sub>2</sub> was injected into the lower stratosphere at four locations outside the equatorial region (30°S, 15°S, 15°N and 30°N) along the 180° longitude band, while in the GeoMIP/G6Sulfur the SO<sub>2</sub> was injected from 10°N to 10°S at 0° longitude. Since the three initiatives use different models (or different versions), climate scenarios, and have their own SAI specifications, we do not directly compare their results but instead present the projected signal from each one.

The extratropical cyclone database used in this study is provided by Reboita et al (2024a), who tracked cyclones south of 20°S in the MSLP field across the three ensemble members of ARISE, GLENS, and GeoMIP/G6Sulfur, with and without SAI. Only cyclones lasting at least 24 hours were considered. Thermal lows - semi-stationary systems - were excluded; their preferential locations over the continents are indicated in **Figure 1**.

For comparison purposes, 6-hourly MSLP and horizontal wind components (with 0.25° of horizontal resolution) from ERA5 reanalysis (Hersbach et al 2020) and precipitation with 1° of horizontal resolution) from the Global Precipitation Climatology Project (GPCP, Huffman et al 2001), developed by the World Climate Research Programme (WCRP), which integrates precipitation data from various sources into a unified final product, were also used.

All datasets (projections, ERA5 and GPCP) were interpolated to the same horizontal resolution of 1.5° x 1.5° with the bi-linear technique (Wahab, 2017, Cerlini et al 2020) before the analysis. Our study periods are: 2015 to 2024 for the reference period, 2040 to 2059 for the near future, and 2080 to 2099 for the far future.

## 2.3 SAI vs no-SAI scenarios

The analyses are divided into three steps: (1) comparison of the precipitation and wind produced by all cyclones in SAI and no-SAI projections, (2) regional analysis of the contribution of cyclones to the total precipitation in SAI and no-SAI projections, as well as the wind intensity, and (3) a brief description of the precipitation and winds based on centered composites of intense cyclones in the austral winter.

### 2.3.1 Precipitation and winds of all cyclones

The precipitation and wind produced by extratropical cyclones were compared between the SAI and no-SAI scenarios. For this purpose, at each stage (timestep) of the cyclones identified in each member of ARISE, GLENS, and GeoMIP/G6Sulfur, the precipitation and wind intensity were selected in an area defined as 8° latitude/longitude on each side of the cyclone center. This number of grid points was chosen to capture the most intense precipitation and wind events that typically occur closer to the cyclone center throughout the system's lifecycle, particularly during the occlusion phase (Reboita et al. 2022; Bartolomei et



al. 2023; Gallottini et al. 2025). Afterwards, an ensemble mean was computed for each initiative. In addition, the cyclone density, i.e., the number of systems in boxes of  $1.5^\circ \times 1.5^\circ$  and standardized by the area of the boxes, was calculated for each project and member at every stage of the cyclone lifecycle. This analysis was included in the cyclone-related precipitation and wind to provide context on whether variations in the number of cyclones correspond to contrasts in the associated precipitation and wind intensity.

### 2.3.2 Regional contribution of cyclones to total precipitation and wind intensity

To give more attention to the surrounding continental regions, we assess the percentage contribution of extratropical cyclones to total precipitation and wind intensity under SAI and no-SAI scenarios for the regions SAO, AFR and AUS (**Figure 1**), the ensemble mean of precipitation or wind intensity produced by cyclones as in **section 2.3.1**, and the average for all time steps (cyclone and non-cyclone) of a given period. The computation was performed at each grid point, and then the mean of the three members of each initiative for the near and far future was taken. The aim is to determine which scenario — SAI or no-SAI — shows a higher percentage contribution of cyclones to the total field of each specific atmospheric variable. Hence, for brevity, we summarize the results showing the difference between SAI and no-SAI. A positive difference indicates that cyclones contribute more to total precipitation/wind intensity under SAI, while a negative difference indicates that the cyclones have more contribution in no-SAI. As in the **section 2.3.1**, the computation was performed for each member and afterwards the mean of the three members of each initiative for the near and far future was taken.

### 2.3.3 Centered Composites

In this approach of centered composites, the idea is to analyse the synoptic structure of the cyclones. Hence, for each subdomain shown in **Figure 1**, and using the cyclone database from Reboita et al (2024a), we

- (a) identified the cyclones that last at least 24 hours within each subdomain;
- (b) determined the time step corresponding to the minimum MSLP during their lifetime within the subdomain;
- (c) compiled all minimum MSLP values identified in (b), ranked them, and calculated the 30th percentile (P30) of this distribution. This percentile was used as a threshold to identify the most intense cyclones;
- (d) selected cyclones with  $MSLP \leq P30$  (step c) to create a subset representing the most intense cyclones (their location in ERA5 is illustrated in **Figure 1**);
- (e) from (d), we performed averages (composites) of MSLP, precipitation and 10-m horizontal wind components, centered on the cyclone's center.

The same methodology was also applied to ERA5 reanalysis.

The composites of MSLP, wind, and precipitation (accumulated at each 6 hours) cover an area extending  $20^\circ$  in all directions from the cyclone center, with the analyses restricted to austral winter (JJA), which is the most cyclogenetic season in the Southern Hemisphere



(Hoskins and Hodges 2005, Reboita et al 2021a,b, 2024b, Zhan and Chen, 2023). The use of a 20° radius allows for capturing the entire spatial structure of the cyclone, including the broader precipitation and wind patterns that often extend beyond 10° (due to the cold and warm fronts) from the cyclone center during its most intense phase, ensuring a more comprehensive representation of the system and its associated impacts (e.g., Reboita et al. 2021b; Cardoso et al. 2025).

### 3. Results and Discussions

#### 3.1. Precipitation and winds produced by cyclones under SAI and no-SAI scenarios

In this section, the precipitation and wind patterns associated with cyclones are compared under SAI and no-SAI scenarios. **Figures 2** and **3** illustrate the differences (SAI - no-SAI) in, respectively, the near and far future periods, and highlight statistically significant differences ( $p < 0.05$ ) based on the non-parametric Mann–Whitney U-test (Mann & Whitney, 1947). Negative values indicate that cyclones produce less precipitation (reddish colors) and weaker winds (greenish colors) under SAI compared to no-SAI scenarios. Additionally, statistically significant differences in cyclone tracking density are indicated by lines, where red (green) lines indicate an increase (decrease) in cyclone tracking density under SAI compared to no-SAI scenarios.

Regarding cyclone track density differences in the near future, SAI scenarios show a higher frequency of cyclones, mainly north of 50°S (**Figure 2a, c, e**). However, in the GeoMIP/G6Sulfur scenario under SAI, a substantial decrease in cyclone frequency also occurs across the South Pacific Ocean and near the Antarctic continent (**Figure 2e**). The signal of increased cyclone frequency becomes clearer in the far future (**Figure 3a, c**). A comprehensive overview of cyclone frequency by latitude band and subdomain in each initiative is presented in **Supplementary Material (Figures SM1, SM2)**.

In the near future, differences in cyclone-associated precipitation between the SAI and no-SAI scenarios, in general, indicate that SAI tends to reduce precipitation south of the subtropics, while north of this region there is no clear pattern — in some areas cyclones are responsible for more precipitation (blue tones) under SAI, while others they produce less precipitation (red tones). Considering the continental areas, which are more important since most of the global population lives on the coast, the ARISE and GLENS (**Figure 2a-c**) under SAI show less precipitation produced by cyclones over parts of South America (particularly southeastern areas), western Australia, and eastern South Africa, with decreases of up to -80%. In contrast, the GeoMIP/G6Sulfur (**Figure 2e**) shows that cyclones in SAI scenarios produce more precipitation over the continents. Although we are describing the results of the three initiatives together, it is important to remember that this is not a performance comparison, as each initiative has its own SAI specifications/protocols (injection latitude/longitude, altitude, start date, duration, and control target), and other features such as host models and physics, and background forcing scenarios. The configurations used in these initiatives help explain the variability in our results. Their design choices determine the spatial distribution of aerosol burden and the resulting radiative gradients, which in turn drive different temperature and pressure gradients. These differences affect wind circulation and lead to distinct Southern Annular Mode (SAM), jet, and storm-track adjustments. For instance, Goddard et al. (2023) showed that different SAI injection strategies (at one or

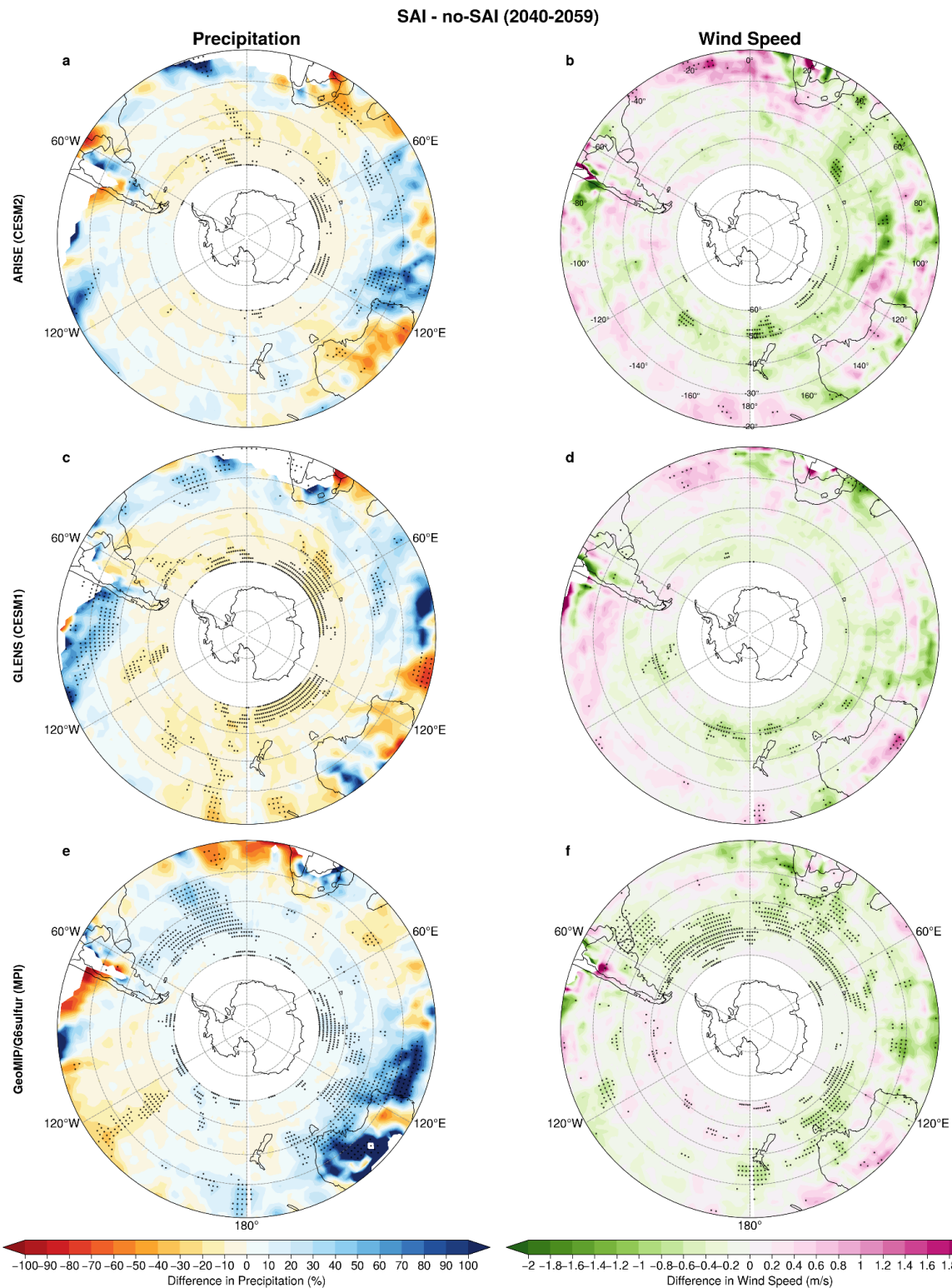


multiple latitudes) result in varying impacts on the Antarctic climate, especially on subsurface ocean temperature and ice accumulation. They observed that the strategy that best minimizes the risk of collapse of parts of the Antarctic ice sheet is highly dependent on how SAI affects the MSLP pattern and wind stress, with implications for the SAM. Additionally, Bednarz et al. (2025) indicate that the SAI's ability to restore or delay the decline of the Atlantic Meridional Overturning Circulation (AMOC) is strongly linked to the latitude of SO<sub>2</sub> injection, and not just to radiative or oceanic processes, which may explain significant differences in how energies are transported and distributed between hemispheres in different simulations (e.g., GLENS vs. ARISE-SAI1.5). In a nutshell, it is possible to associate the different responses in precipitation and wind associated with extratropical cyclones with the different SAI strategies that each model employs, since this directly impacts circulations and, consequently, cyclone formation.

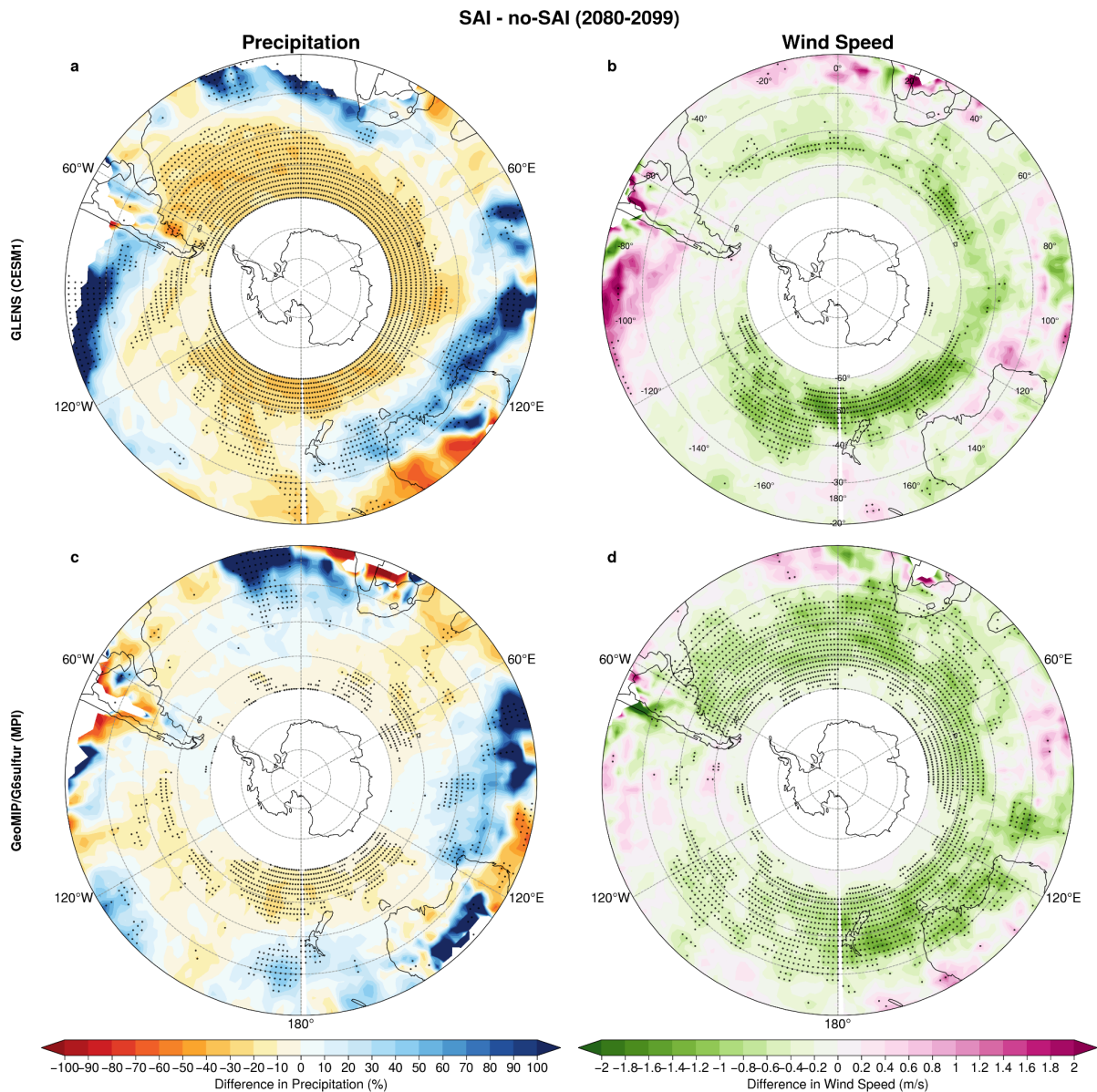
When comparing differences in precipitation and wind in the near future (**Figure 2**), there is no strong relationship indicating that lower precipitation amounts are always associated with weaker winds, which would be expected based on the cyclone's physics. In some regions, less precipitation under SAI occurs in the same areas of weaker winds, while in others, it is linked to stronger winds. In a general analysis of the wind differences, the projected wind pattern generally is weaker south of the subtropics and over the continent (by up to  $-2 \text{ ms}^{-1}$ , significantly values) under SAI scenarios.

While in the near future (**Figure 2**) the projected precipitation and wind intensity signals are sometimes interchanged, a more robust pattern emerges in the far future (**Figure 3**): both precipitation and wind decrease toward Antarctica under both SAI scenarios available for this period, and a clearer relationship is observed between the two variables, with regions experiencing simultaneous increases or decreases in both. While GLENS under SAI shows larger areas with bigger changes in precipitation than in wind intensity, the opposite occurs for GeoMIP/G6Sulfur. For precipitation, GLENS (**Figure 3a**) shows a significant decrease in the cyclonic contribution over a broad area of the Southern Oceans, especially at mid-latitudes. In addition, there is less precipitation northeast of Australia, and across the east coast of South America. GeoMIP/G6Sulfur (**Figure 3b**) also has a similar spatial pattern in the signal of the differences but weaker in intensity. For wind speed (**Figure 3c-d**), in general, GLENS and GeoMIP/G6Sulfur project decrease in the wind intensity near the coastal regions under SAI scenario.

This section highlights that the effects of SAI on the climate system become more pronounced and systemic over time. This difference is likely due not only to the longer duration of SAI deployment, but more critically to the increase in injection magnitude over time in these scenarios due to cooling targets, leading to a stronger signal-to-noise ratio or circulation impacts that vary non-linearly with induced cooling. The decrease in wind intensity suggests that SAI scenarios may reduce wind-related impacts associated with cyclones. These findings complement those of Reboita et al (2024a), which indicate that SAI helps offset the impact of global warming on extratropical cyclones. SAI may lead to a general decrease in their frequency, a weakening in terms of MSLP, and/or a shift in their tracks to more closely resemble those of the reference period.



**Figure 2** Relative difference in precipitation (% , left column) and absolute difference in wind intensity ( $\text{ms}^{-1}$ , right column) produced by extratropical cyclones for the near future (2040-2059) between SAI and no-SAI. Black dots indicate statistical significance ( $p < 0.05$ ) based on the non-parametric Mann–Whitney U-test.



**Figure 3** Similar to Figure 2, but for the period 2080–2099.

### 3.2. Contribution of cyclones to precipitation and wind intensity under SAI and no-SAI scenarios

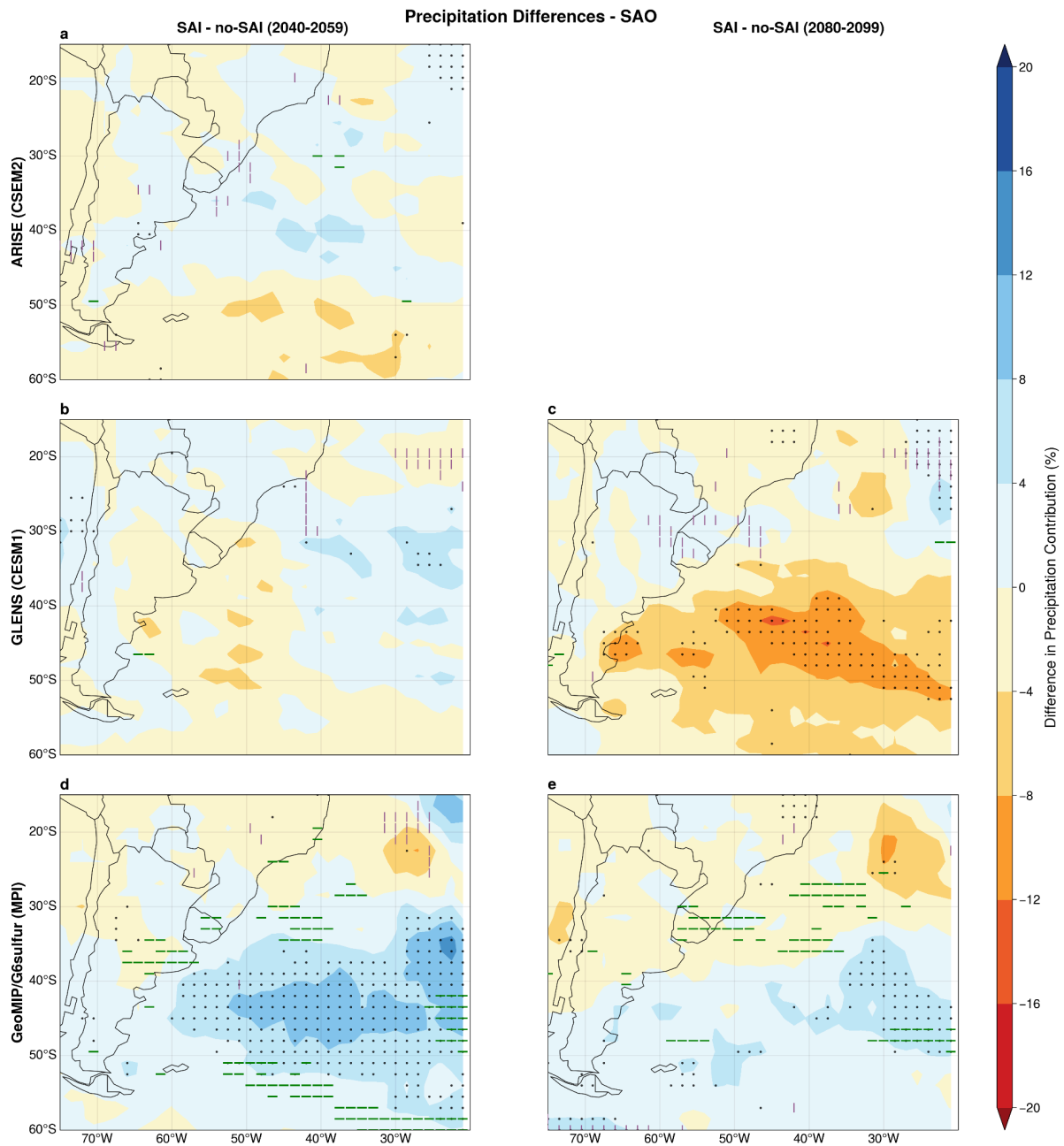
**Figures 4–6** present the annual differences between SAI and no-SAI in the percentage contribution of precipitation and wind intensity from extratropical cyclones relative to the total fields for the SAO, AFR, and AUS subdomains (as defined in **Figure 1**). Precipitation differences are represented by shaded areas, with statistically significant values are indicated by black dots, while areas with statistically significant differences in the wind intensity are marked with purple vertical markers indicating positive and green horizontal markers indicating negative differences, all based on a non-parametric Mann–Whitney U-test ( $p < 0.05$ ). To support the analysis of the results, **Figures SM3–8** show the contribution of cyclones to total precipitation and winds by presenting the annual relative contributions of both SAI and no-SAI scenarios separately.



Over the SAO (**Figure 4**), for the near future, all three initiatives indicate a mixed signal of cyclones contribution to total precipitation under SAI and no-SAI over the South Atlantic Ocean and South America with no statistically significant signal (**Figure 4a, b, d**), except for GeoMIP/G6Sulfur in a few areas over the continent (e.g.  $\sim 20^{\circ}\text{S}$ ;  $50^{\circ}\text{W}$  and  $46^{\circ}\text{S}$ ;  $70^{\circ}\text{W}$ ) and in a vast region over the South Atlantic (from  $60^{\circ}$ - $20^{\circ}\text{W}$ ) indicating more contribution of cyclones to precipitation under SAI scenario (**Figure 4d**). In the far future, GeoMIP/G6Sulfur maintains a similar spatial pattern of precipitation difference but weaker compared to near future, suggesting that the contribution of cyclones to total precipitation decreases by the end of the century under SAI scenario (**Figure SM3j, l**). On the other hand, GLENS (**Figure 4b**) shows a predominance of negative differences, indicating less contribution to the total precipitation from cyclones under SAI scenario over almost the whole SAO domain, with stronger signal south of  $35^{\circ}\text{S}$ . All projections show stronger contribution of cyclones to the total wind intensity field around  $20^{\circ}\text{S}$ - $45^{\circ}\text{W}$  under SAI scenario compared to no-SAI (**Figure 4**). It is important to highlight that this is one of the cyclogenetic regions in the South American continent and a hotspot of subtropical cyclone genesis (de Jesus et al 2021, Reboita et al 2024b). On the other hand, GeoMIP/G6Sulfur shows less contribution of cyclones to wind intensity in the latitudinal band of  $25^{\circ}$ - $45^{\circ}\text{S}$  over the continent and along the coast (**Figure 4d, e**), which is also a cyclogenetic region, indicating weaker winds associated with cyclones under SAI scenario compared to no-SAI.

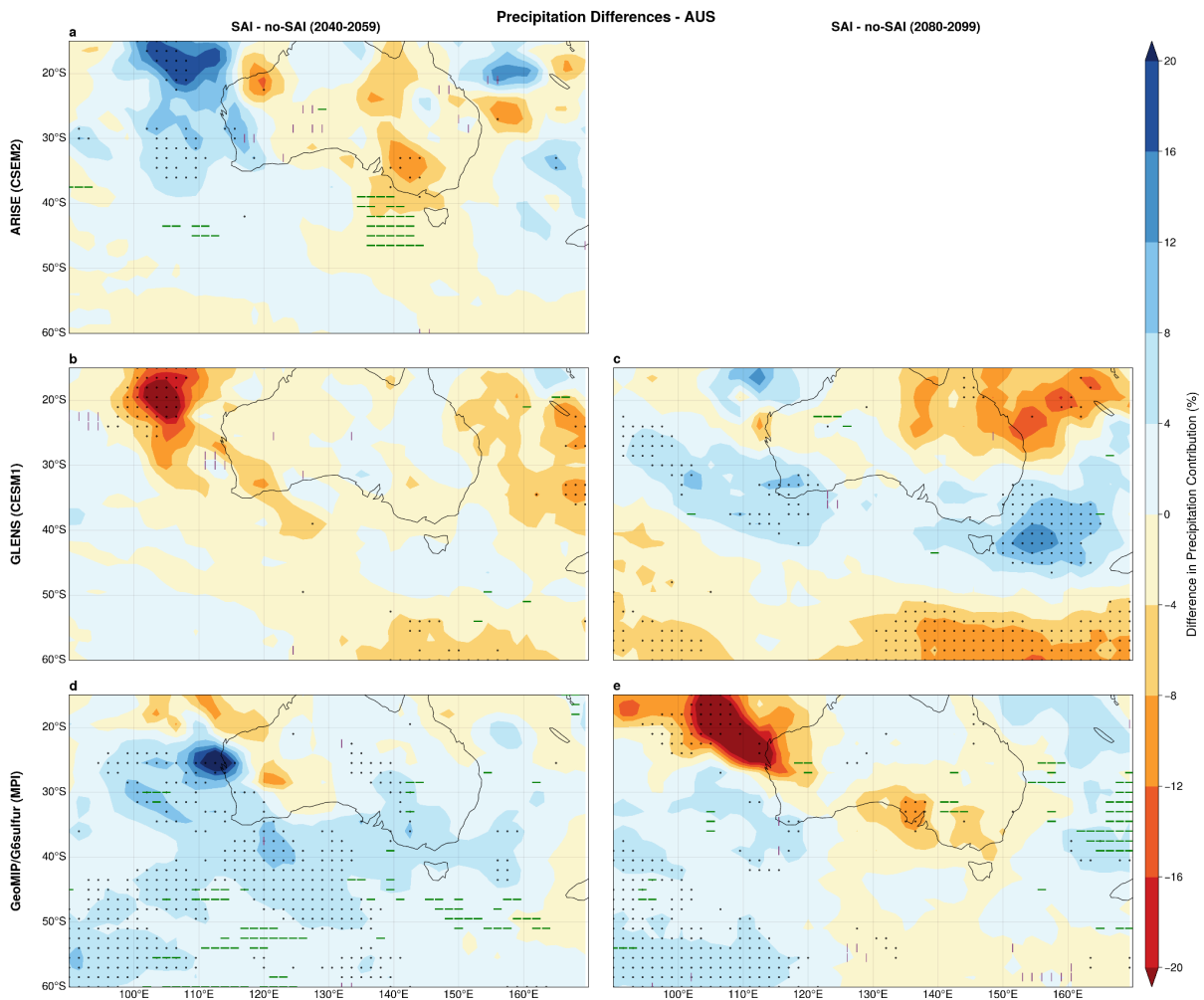
Over the AFR subdomain in the near future there is also a mixed pattern in the contribution of the cyclones to the total precipitation. In the region between southeastern Africa and Madagascar, ARISE and GLENS indicate that cyclones under SAI have less contribution to total precipitation than under no-SAI (**Figure 5a, b, d**), but this signal only becomes visible in the far future for GeoMIP/G6Sulfur (**Figure 5e**). GLENS shows a great statistically significant area south of  $40^{\circ}\text{S}$  with less contribution from cyclones to precipitation under SAI scenario (**Figure 5c**), whereas GeoMIP/G6Sulfur shows negative differences for the same latitudinal band but from  $20^{\circ}\text{W}$  to  $20^{\circ}\text{E}$  (**Figure 5e**). Statistically significant positive differences of cyclones contribution to wind intensity are seen in the northwestern part of the AFR domain in all initiatives (**Figure 5**) but negative differences are only consistent in GeoMIP/G6Sulfur, where a larger area is pronounced in the far future (**Figure 5e**). Hence, indicating less contribution of cyclones to wind intensity southern  $30^{\circ}\text{S}$  under SAI scenarios.

In the AUS subdomain (**Figure 6**), the evolution of the spatial pattern of the precipitation differences between near and far future in the three initiatives is less consistent compared to the SAO and AFR regions. For instance, in the near future, ARISE (**Figure 6a**) shows statistically significant contribution of cyclones under SAI scenario to total precipitation in western Australia and the opposite over the southern part of the continent. Conversely, GLENS (**Figure 6b**) presents an opposite spatial pattern, and in GeoMIP/G6Sulfur (**Figure 6d, e**) this occurs in the near future. Overall, there is a statistically significant increased contribution of cyclones to total precipitation over southwestern Australia under SAI scenarios and less contribution over south and northeastern part in different time slices and initiatives. Over Australia, the initiatives agree on a higher contribution of cyclones to wind intensity in the near future (**Figure 6a, b, d**) and in the southern part in the far future under SAI scenario (**Figure 6d, e**).



**Figure 4** Annual differences of the relative contribution of extratropical cyclones to the total precipitation and 10-m wind intensity between SAI and no-SAI for the SAO region for near (**a**, **b**, **d**) and far (**c**, **e**) futures in each initiative relative to present. Black dots indicate statistically significant differences in precipitation contribution, purple vertical markers indicate positive and green horizontal markers indicate negative statistically significant differences in wind intensity. Statistical significance is based on the non-parametric Mann–Whitney U-test at  $p < 0.05$ .





**Figure 6** Similar to **Figure 4**, but for the AUS region.

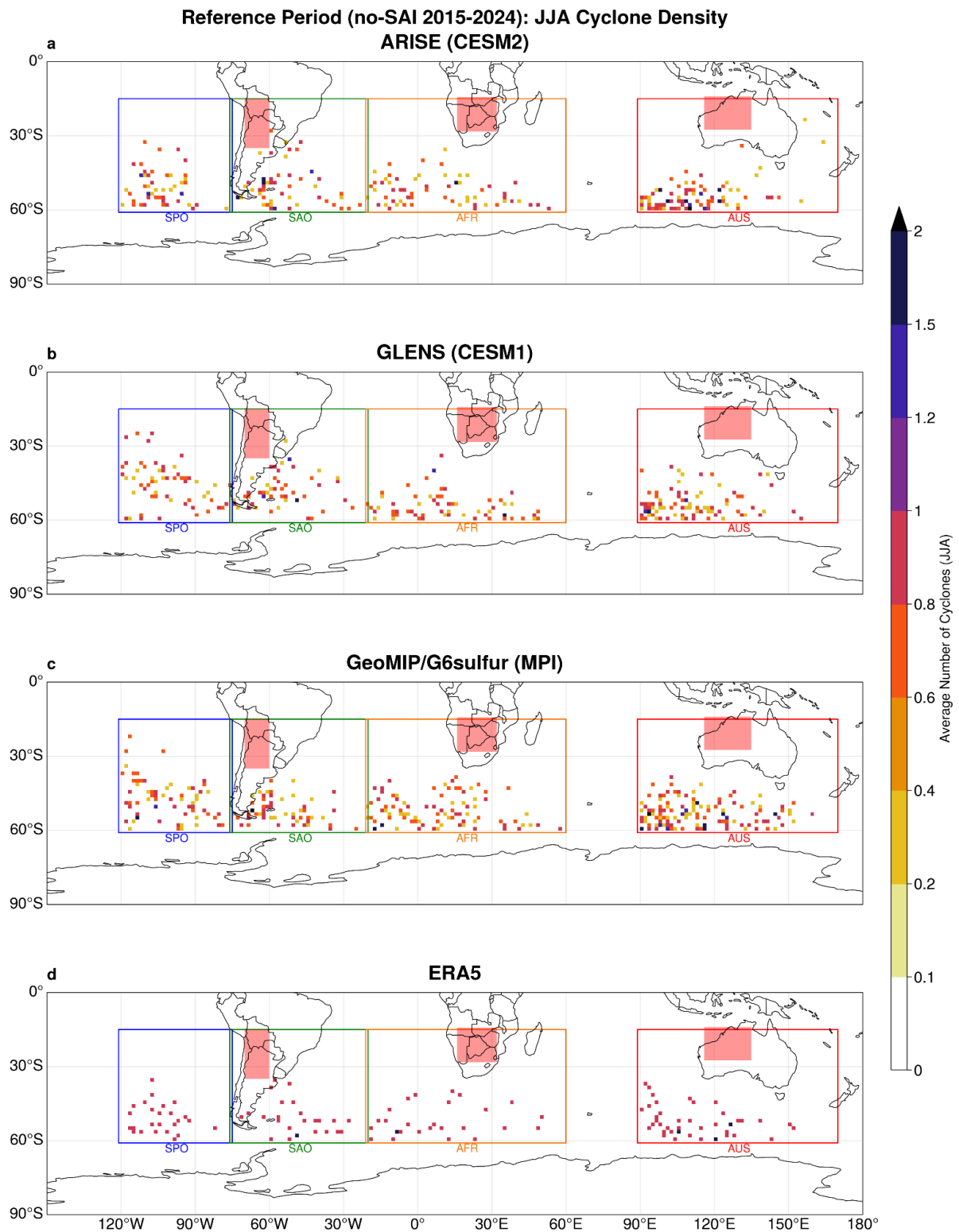
Interpreting changes in the relative contribution of cyclones to total precipitation and wind intensity requires careful analysis of both cyclone-related changes and background changes (non-cyclone-related, **Figures SM10-15**). The decrease in cyclonic fraction observed in some regions (e.g., precipitation in southern South America, continental Africa, and Madagascar, mainly in ARISE and GLENS and in GeoMIP/G6Sulfur in the distant future) may be the result of the documented weakening of cyclonic activity under SAI (as shown in **Section 3.1**), or it may stem from an increase in non-cyclonic precipitation or wind, or a combination of both effects. For example, an increase in non-cyclonic precipitation - potentially driven by greater mean moisture convergence or changes in local convection - would dilute the relative contribution of cyclones, even if absolute cyclone-related precipitation remained constant. Although a detailed decomposition of cyclonic and non-cyclonic contributions is beyond the scope of this article and is relegated to the Supplementary Material for reference (**Figures SM9-14**), this dual dependence highlights the complexity of regional SAI impacts, where changes in large-scale circulation not only modulate cyclone intensity and tracking but also affect background meteorological fields.

### 3.3. Intense extratropical cyclones during austral winter



The two previous sections discussed the contribution of cyclones to precipitation and wind intensity, considering all cyclone types (both weak and strong). In this section, we provide a general overview of how the most intense systems respond to SAI.

The time step at which the most intense cyclones (MSLP < P30) reach their greater intensity was identified for each initiative member, and an ensemble was created for JJA (2015–2024); the same analysis was performed using ERA5 (**Figure 7**). The highest frequency of intense cyclones is observed in the southernmost regions of the Southern Hemisphere, particularly between 40°S and 60°S (**Figure 7**), in the storm tracks preferential location (Jones and Simmonds, 1993, Mendes et al 2009, Reboita et al 2010, Sinclair and Dacre, 2019). The most notable result in **Figure 7** is that the time step at which cyclones reach their greater intensity occurs near the coast exclusively in the SAO region, specifically along the eastern coast of South America. This highlights that, among the three continental regions analyzed, South America appears to be the most exposed and potentially vulnerable to the impacts of intense cyclones. Indeed, Reboita et al (2021b) showed that the coasts of Uruguay and southern Brazil are preferential zones for the development of explosive cyclones, further emphasizing the region's susceptibility to high-impact weather systems.



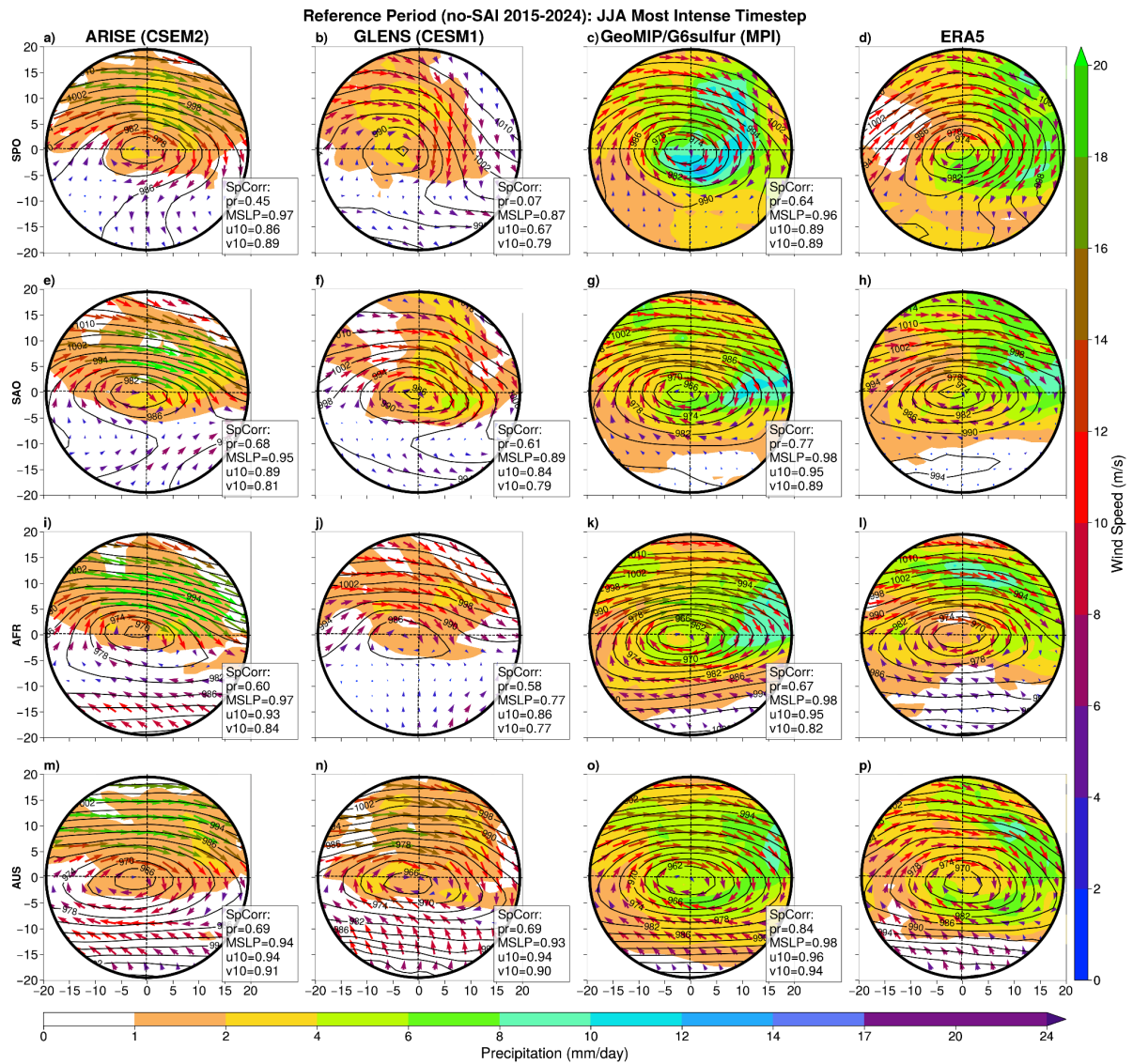
**Figure 7** Average number of intense cyclones (sum within  $1.5^\circ \times 1.5^\circ$  grid boxes) for each subdomain during JJA for the reference period (2015–2024) in: **a)** ARISE, **b)** GLENS, **c)** GeoMIP/G6Sulfur, and **d)** the ERA5 reanalysis.



**Figure 8** shows the synoptic pattern of the centered averages for the reference period of MSLP, 10-m wind intensity, and precipitation, during the maximum intensity of the most intense cyclones in each initiative and ERA5/GPCP, and in each subdomain. At first glance, it is evident that the strongest winds occur in the northeast quadrant of the cyclones, while precipitation is concentrated in the center to eastern-southeastern regions in all subdomains and initiatives (**Figure 8**). This pattern aligns with the typical structure of extratropical cyclones (Emanuel et al 2024, Cardoso et al 2025) and explosive cyclones (Reboita et al 2021b), where there is greater precipitation in general along the warm front as a response to the strong winds from the cold to warm front, i.e., in the northeast sector of the system. Even though there is an agreement in the spatial pattern between initiatives and reanalysis (spatial correlation is shown in **Figure 8**), both GLENS and ARISE underestimate the wind intensity and accumulated precipitation, while GeoMIP/G6Sulfur show values closer to, or higher than ERA5/GPCP. This is somewhat in line with findings from Cardoso et al (2025), who carried out a similar analysis comparing cyclones projected in high and medium resolution from HighResMIP-Coupled Model Intercomparison Project 6. They found that MPI-ESM1-2 (same model in GeoMIP/G6Sulfur) simulates a cyclone center with lower MSLP (~1-2 hPa), and with higher wind intensity and precipitation compared to ERA5 and CFSR reanalysis slightly eastward of the cyclone center.

To quantitatively assess the ensembles' performance against ERA5/GPCP, we computed spatial correlations (**Figure 8**). The results show that the ensemble for each initiative correlates highly with ERA5 in pressure and wind components, with values above 0.77 across all regions and initiatives—except for u10 in GLENS/SPO, which had a correlation of 0.67. These results indicate that the models reliably capture synoptic patterns relative to ERA5. Precipitation correlations are also strong, exceeding 0.58 in most cases, except for ARISE (0.45) and GLENS (0.07) in SPO.

When we compared the subdomains of a specific project, there are some differences in the spatial pattern of the composites. For instance, ARISE (**Figure 8a-d**) simulates cyclones with central MSLP values of 974, 978, 978, and 982 hPa in the AUS, SPO, AFR, and SAO regions, respectively. However, this does not necessarily mean that cyclones over AUS will have the most intense winds over the whole subdomain. Wind intensity depends on the horizontal pressure gradient force (i.e., the rate of MSLP change over a given distance). As the horizontal pressure gradient is steeper in the eastern side (between northern and southern quadrants) in the AFR domain than in AUS and the other subdomains, the winds are more intense for AFR in that sector. Regarding precipitation, while SPO, SAO, and AFR exhibit a core of more intense precipitation between the cyclone center (occluded sector) and its eastern part (warm front), AUS presents a broader area of weaker precipitation compared to the other regions. These regional features are also simulated by GLENS (**Figure 8e-h**) and GeoMIP/G6Sulfur (**Figure 8i-l**).



**Figure 8** Centered averages of MSLP (hPa; lines), 10-m wind ( $\text{ms}^{-1}$ , arrows) and precipitation ( $\text{mm day}^{-1}$ ; shaded) during the maximum intensity of cyclones occurring in **a-d**) SPO, **e-h**) SAO, **i-l**) AFR, and **m-p**) AUS for ARISE (first column), GLENS (second column), GeoMIP/G6Sulfur (third column), and ERA5 (last column, GPCP daily precipitation) between 2015-2024. Note that the axes of the maps do not represent actual cyclone coordinates but rather distances (in degrees) from the cyclone center. The bottom right boxes represent the spatial correlation (SpCorr) between the different simulated variables and ERA5/GPCP.

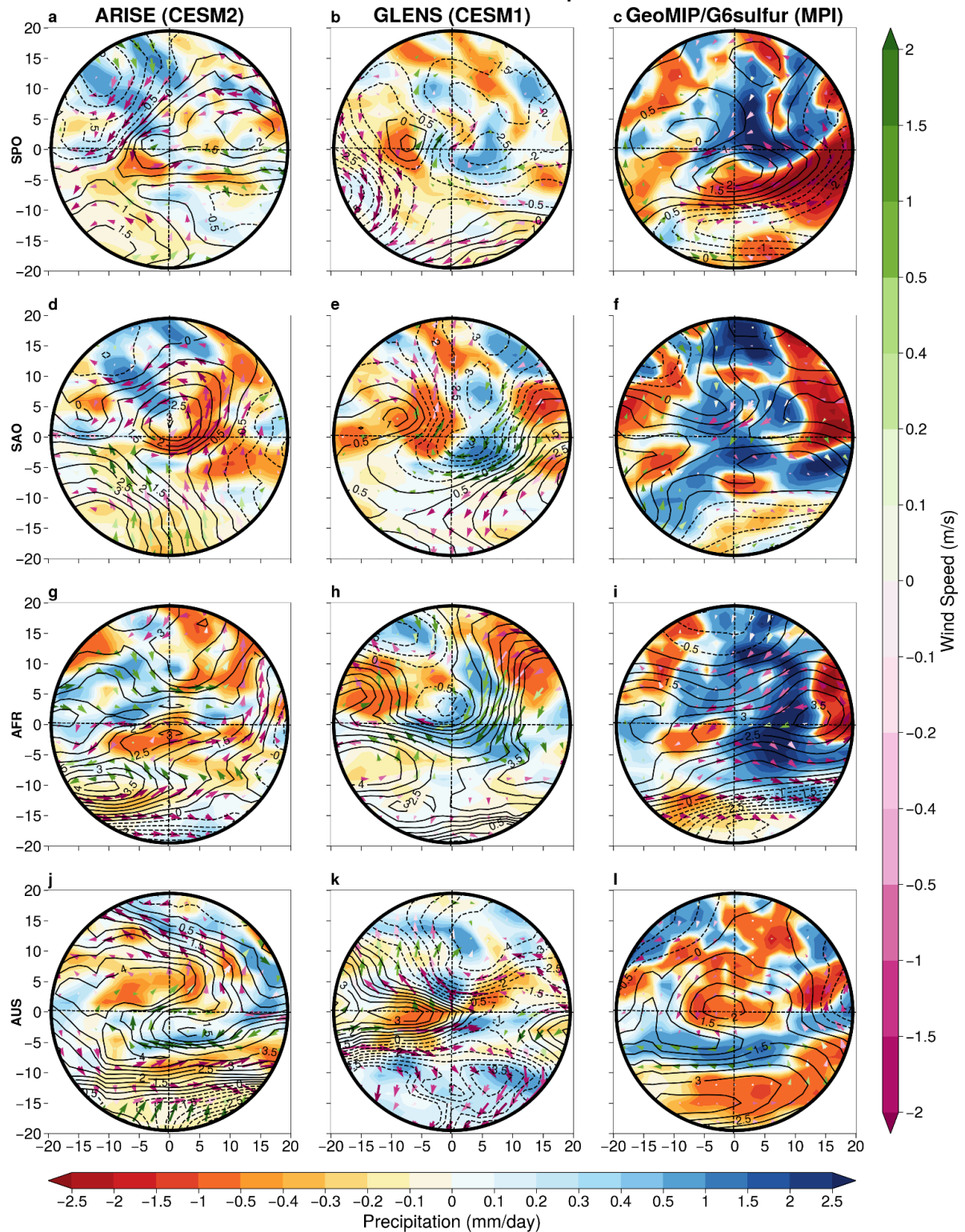


When comparing the composite differences between SAI and no-SAI scenarios for the near future (2040–2059) across subdomains and the three initiatives (**Figure 9**), it becomes evident that the distinct models (and their random variability) and experimental designs of ARISE, GLENS, and GeoMIP/G6Sulfur contribute to divergent regional responses to SAI under climate change scenarios. One clear example of this variability is seen in the spatial distribution of the most intense wind differences. While ARISE (**Figure 9a, d, g, j**) and GLENS (**Figure 9b, e, h, k**) generally show predominance of weakening of 10-m winds in all subdomains under SAI, the differences between SAI and no-SAI are weaker in GeoMIP/G6Sulfur (**Figure 9c, f, i, l**). Another distinction among the ensembles is the sector of the cyclones with strong or weak winds in SAI scenarios. For instance, in AFR, at the northeast quadrant of the cyclone, ARISE shows an east-west gradient from more intense to weaker winds, while in GLENS they are stronger under SAI and in GeoMIP/G6Sulfur they are weaker under SAI compared to no-SAI. Considering precipitation, the most obvious feature in **Figure 9** is that the magnitude of the differences is greater in GeoMIP/G6Sulfur than in the other two initiatives. This is despite the SAI forcing being less than the others. It is an important point that really must indicate the difference in SAI strategy between the three initiatives, while also recognizing that ARISE and GLENS share a common model lineage (CESM) whereas GeoMIP/G6Sulfur employs a different model (MPI-ESM1-2-LR), meaning the magnitude differences could be partially attributable to distinct model physics or resolution. Still considering precipitation, ARISE and GLENS indicate a decrease in this variable near the cyclone core under SAI in SAO, whereas GeoMIP/G6Sulfur presents an increase. In contrast, other subdomains show more consistent spatial signals among the initiatives. In SPO and AFR, SAI scenarios tend to project increased precipitation in the east-central sectors of the cyclones compared to no-SAI conditions. In the AUS region, the three ensembles show enhanced precipitation anomalies under SAI to the midwest of the cyclone center.

The spatial pattern of the analyzed variables is more similar in the far future (**Figure 10**) than in the near future (**Figure 9**) for GLENS and GeoMIP/G6Sulfur. Even though, we highlight some differences shown in **Figure 10**: GLENS indicates weaker extratropical cyclones under SAI, characterized by increased MSLP (except for SAO), reduced 10-meter wind intensity, and suppressed precipitation near cyclone centers across all subdomains (**Figure 10a, c, g, e**). Additionally, the spatial pattern of these differences is particularly well-defined over the SPO region, where wind weakening is concentrated directly over the cyclone center (**Figure 10a**).

The differences in synoptic patterns between SAI and no-SAI scenarios are more difficult to interpret, as even small changes in atmospheric circulation can significantly modify pressure gradients and moisture convergence. It is noted that the SAI strategy—specifically the latitude of aerosol injection (e.g., Northern Hemisphere focused on GLENS, Southern Hemisphere focused on ARISE, and Equatorial in GeoMIP/G6Sulfur)—is known to differentially impact atmospheric circulation in the Southern Hemisphere (e.g., through the Southern Annular Mode). While these fine-scale dynamics are important, a detailed investigation of their mechanisms falls beyond the scope of the present study. Future work could explore how these hemispheric forcing asymmetries translate into the observed regional differences in cyclone synoptic patterns, particularly regarding the pressure gradients and moisture transport over the Southern Ocean and adjacent continental areas.

Near-Future (2040-2059): SAI - no-SAI  
JJA Most Intense Timestep



**Figure 9** Difference in composites between SAI and no-SAI (2040-2059) of MSLP (hPa; lines), 10-m wind (ms<sup>-1</sup>, arrows) and precipitation (mm day<sup>-1</sup>; shaded) during the maximum intensity of cyclones occurring in a-c) SPO, d-f) SAO, g-i) AFR, and j-l) AUS for ARISE (first column), GLENS (second column), and GeoMIP/G6Sulfur (third column).

Far-Future (2080-2099): SAI - no-SAI  
JJA Most Intense Timestep

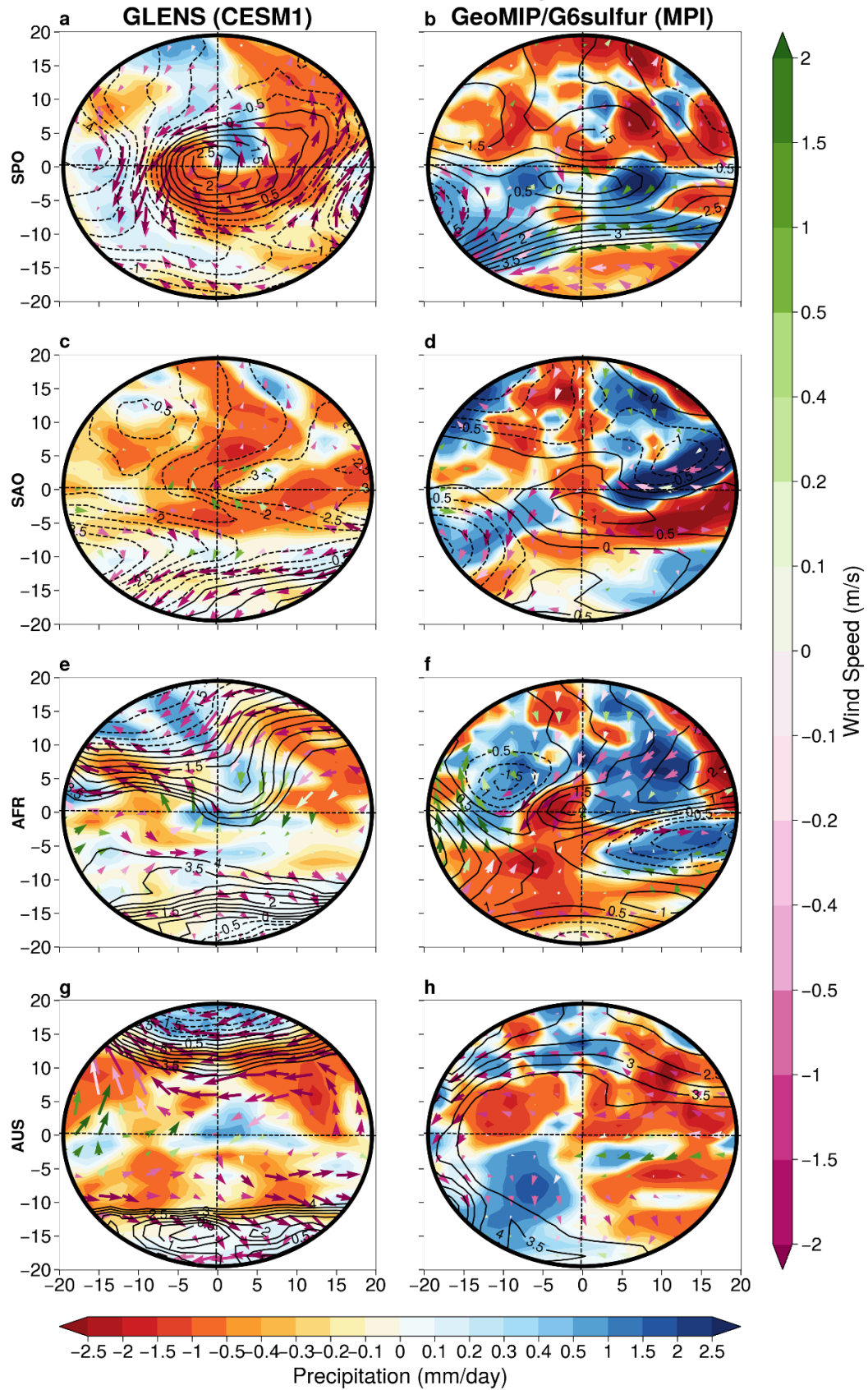


Figure 10 Similar to Figure 9, but for the period 2080–2099.



#### 4. Conclusions

This study aimed to assess the impact of SAI on the precipitation and 10-m wind intensity caused by extratropical cyclones in the Southern Hemisphere under future climate change scenarios, using data from three international modeling initiatives: ARISE, GLENS, and GeoMIP/G6Sulfur. The main findings of this study are:

*Precipitation and winds produced by cyclones under SAI and no-SAI scenarios:* in an annual analysis, SAI generally leads to a weakening of both precipitation and 10-m wind intensity associated with cyclones when compared to no-SAI scenarios.

*Percentage contribution of cyclones to total precipitation and wind intensity:* the regional analyses (SAO, AFR, AUS) revealed that, under SAI scenarios, the contribution of extratropical cyclones to both total precipitation and wind intensity generally decreases from the near to far future, with the most pronounced reduction appearing in the GLENS. However, it is important to highlight that the impacts of SAI are not totally uniform across the subdomains and initiatives. For instance, GeoMIP/G6Sulfur shows increased cyclone contributions to precipitation in parts of SAO, while ARISE exhibits increases in precipitation contribution over western Australia.

*Intense extratropical cyclones during austral winter:* composite analyses provided insights into the synoptic structure of the most intense cyclones under SAI and no-SAI scenarios. While GLENS presented coherent spatial patterns indicating suppressed cyclone intensity across all subdomains (except for SAO), GeoMIP/G6Sulfur showed greater spatial variability, including shifts in wind and precipitation quadrants. GeoMIP/G6Sulfur also depicted the largest SAI–no-SAI differences in precipitation; this is noteworthy because its SAI forcing is weaker than the others, which may underscore distinct strategic approaches among the three initiatives, or alternatively, be a result of the unique characteristics of the MPI-ESM1-2-LR model compared to the CESM variants used by the other ensembles. These findings suggest that SAI effects are not spatially uniform and may drive regional reorganization of cyclone dynamics.

Although this study has provided a comprehensive analysis of the large-scale impacts of SAI on cyclone characteristics within global climate models, future work could focus on investigating individual cyclonic systems in SAI scenarios, particularly using high-resolution regional climate models. This would be highly valuable for capturing details of localized changes in precipitation and wind (e.g., changes in cyclone intensity near the coast), as greater detail could help quantify these differences in key locations. However, it is important to recognize that applying regional modeling to SAI remains challenging, given the need for appropriate downscaling techniques and the computational demands of accurately representing the stratospheric aerosol layer in regional settings. It is important to emphasize that the SAI experiments considered here employ substantially different intervention protocols, particularly with regard to the latitude of SO<sub>2</sub> injection and the total magnitude of radiative forcing. These differences mean that the initial aerosol plumes are introduced into the stratosphere at distinct locations, where specific atmospheric circulation patterns determine their subsequent transport and dispersion. This results in spatially unique distributions of stratospheric aerosols for each initiative. The resulting changes in large-scale atmospheric circulation (especially its response at low levels) will consequently affect extratropical cyclones differently between the sets. Therefore, complete similarity in the



projected impacts on cyclone precipitation and wind intensity across different SAI initiatives is not expected, highlighting that regional and global climate responses are highly dependent on strategy.

The main message of this study is that in the Southern Hemisphere, SAI under global warming brings cyclone precipitation and wind intensity closer to the historical climate. However, the study must consider uncertainties related to models, their configurations, and SAI implementation strategies. Although SAI may be a promising tool for alleviating climate change impacts, its deployment requires ongoing, comprehensive assessments that weigh both potential benefits and unintended consequences for regional and global scales.

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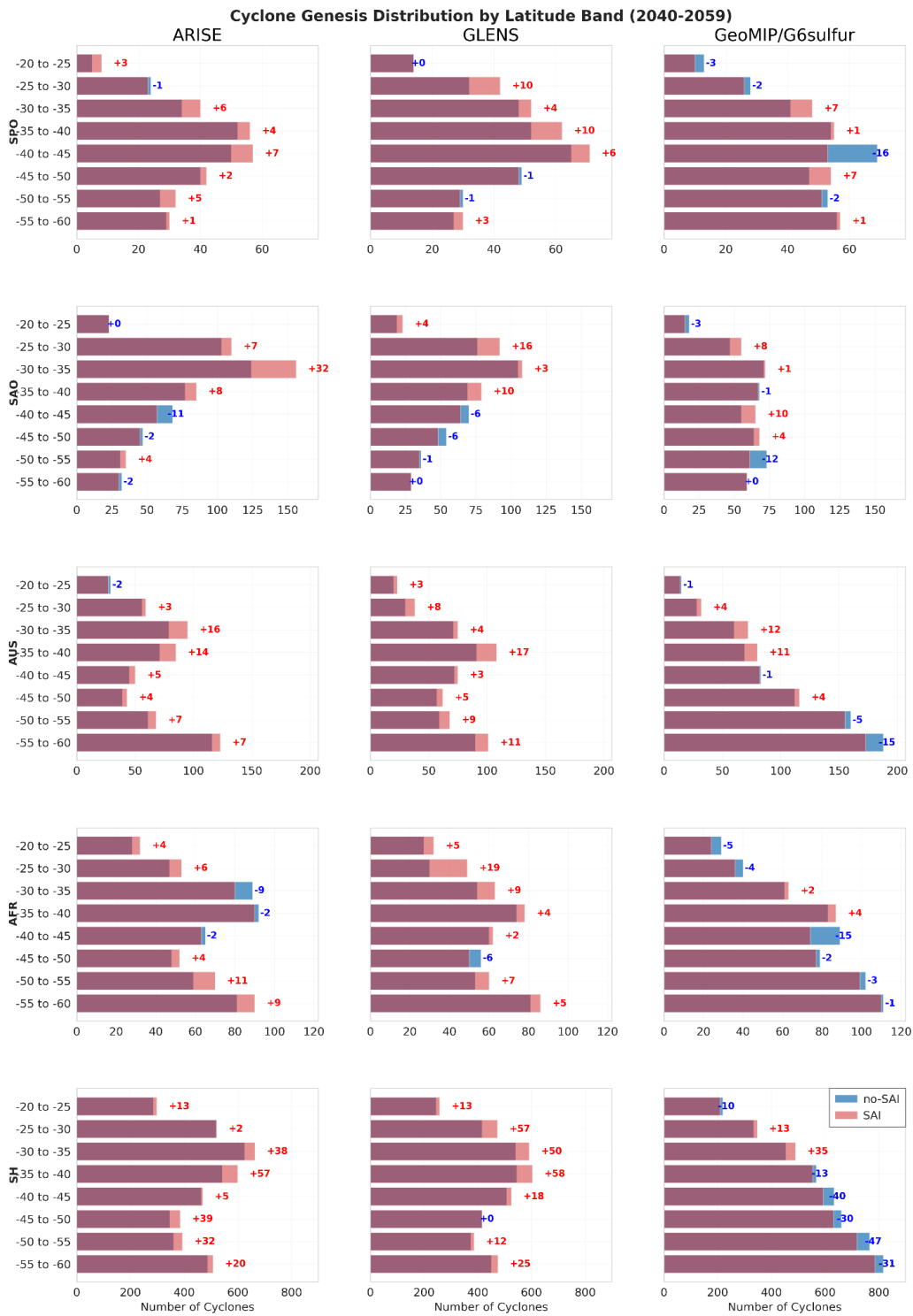
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## Supplementary Data 1: Additional information on Distribution of cyclones, precipitation, and wind

It is important to note the number of extratropical cyclones generated in the Southern Hemisphere at each latitude band. We have included a comparison of this metric between SAI (red bars) and no-SAI (blue bars) for the near future (2040-2059, **Figure SM1**) and far future (2080-2099, **Figure SM2**). In these figures, each column represents a model and each row represents a specific region: Southeast Pacific Ocean (SPO), Southwest Atlantic Ocean (SAO), Southern Africa (AFR), and Australia (AUS); and the last row represents the total amount for the Southern Hemisphere.



**Figure SM1** Number of cyclones in the near future by latitude band in the subdomains SPO, SAO, AFR, and AUS, and in the whole Southern Hemisphere (SH) in austral winter (JJA). From left to right: ARISE, GLENS and GeoMIP/G6Sulfur. The numbers on the right side of the bars indicate the difference in frequency between SAI and no-SAI.

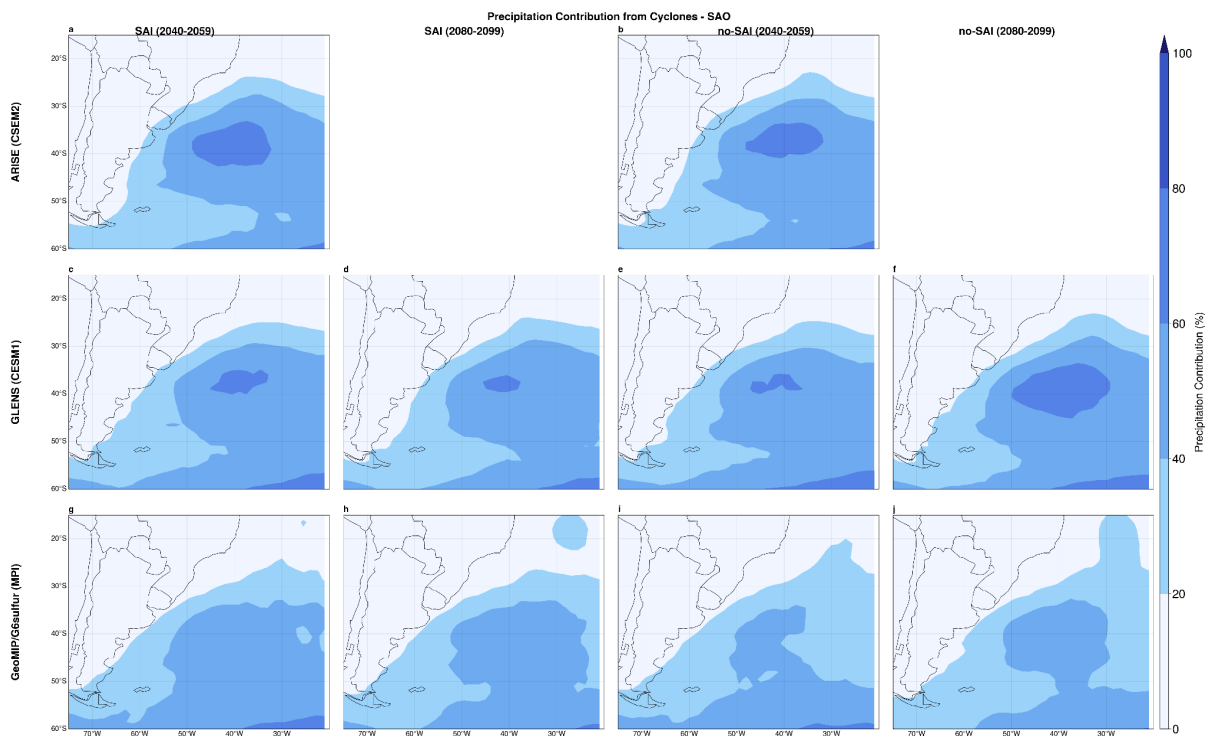


### Cyclone Genesis Distribution by Latitude Band (2080-2099)

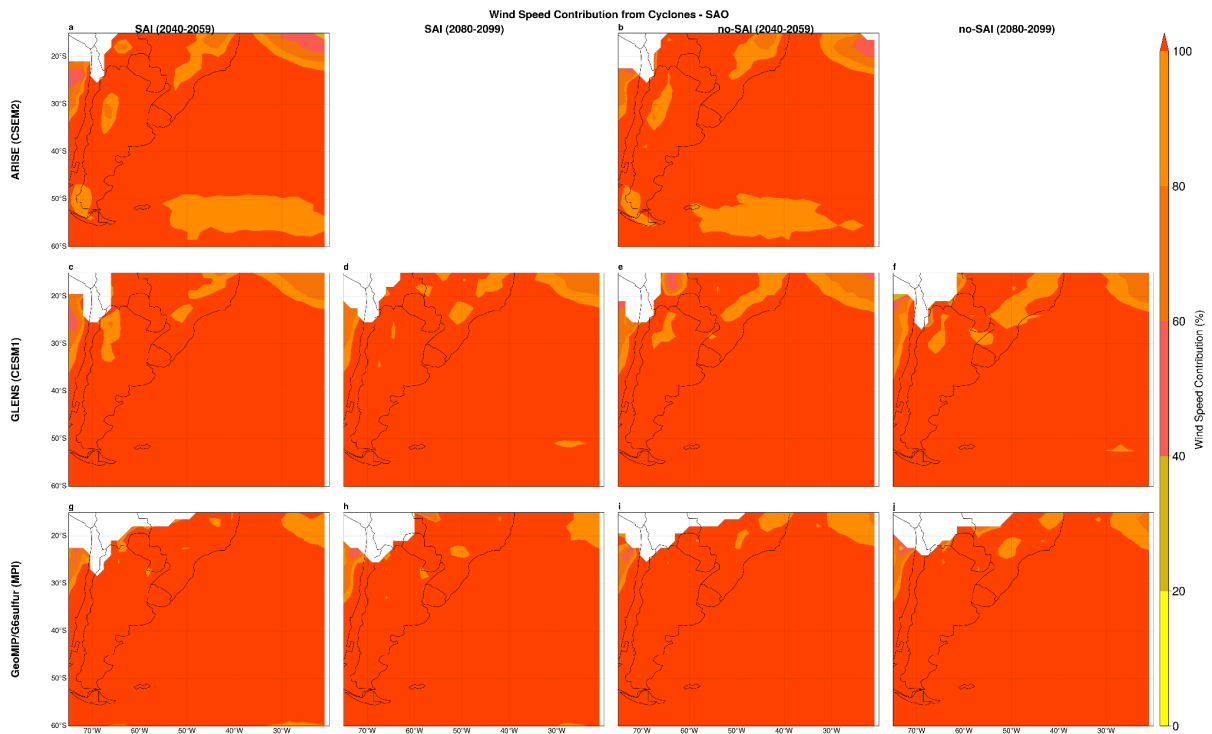


Figure SM2 Similar to Figure SM1, but for the period 2080–2099.

For each region studied, it was important to observe the individual characteristics of the contribution of extratropical cyclones relative to experiments with and without SAI. To this end, **Figure SM3** shows the relative annual contribution of precipitation produced by extratropical cyclones to the SAO region. With contributions above 20% in coastal regions of the extreme south of South America and southern Brazil (except GeoMIP/G6Sulfur) for both experiments. The contribution of wind speed (**Figure SM4**) shows that extratropical cyclones have values above 100% in much of the continental region. Values above 100% indicate that winds are stronger during extratropical cyclones than the annual average.

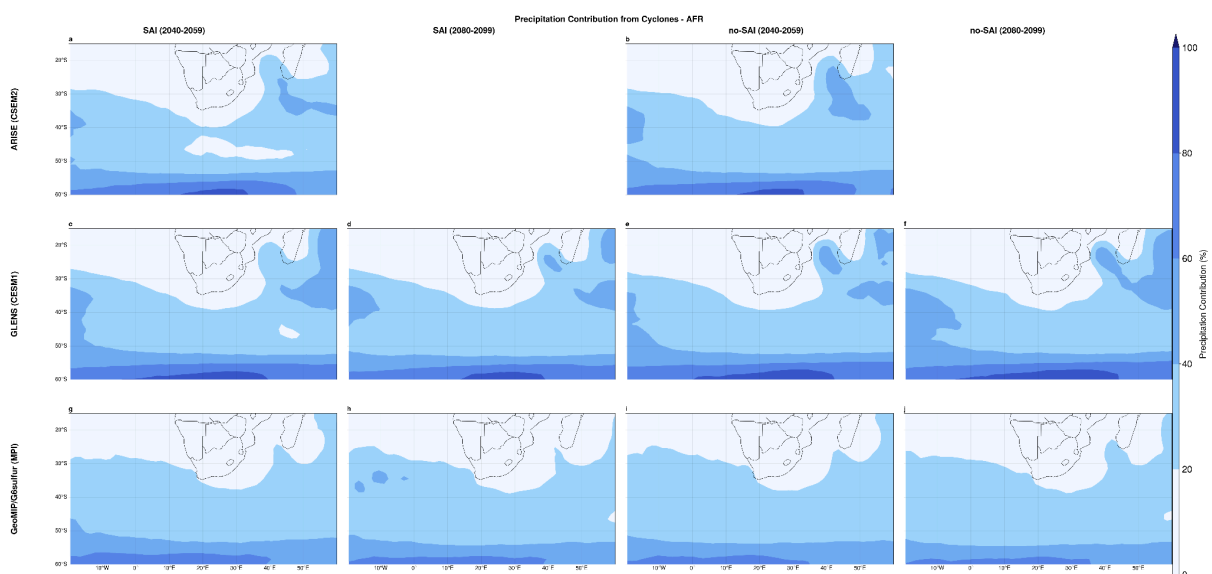


**Figure SM3** Annual relative contribution (%) of extratropical cyclones to the total precipitation under (a, c, f, i, j) SAI and (c, g, h, k, l) no-SAI for the SAO region for the near and far future.

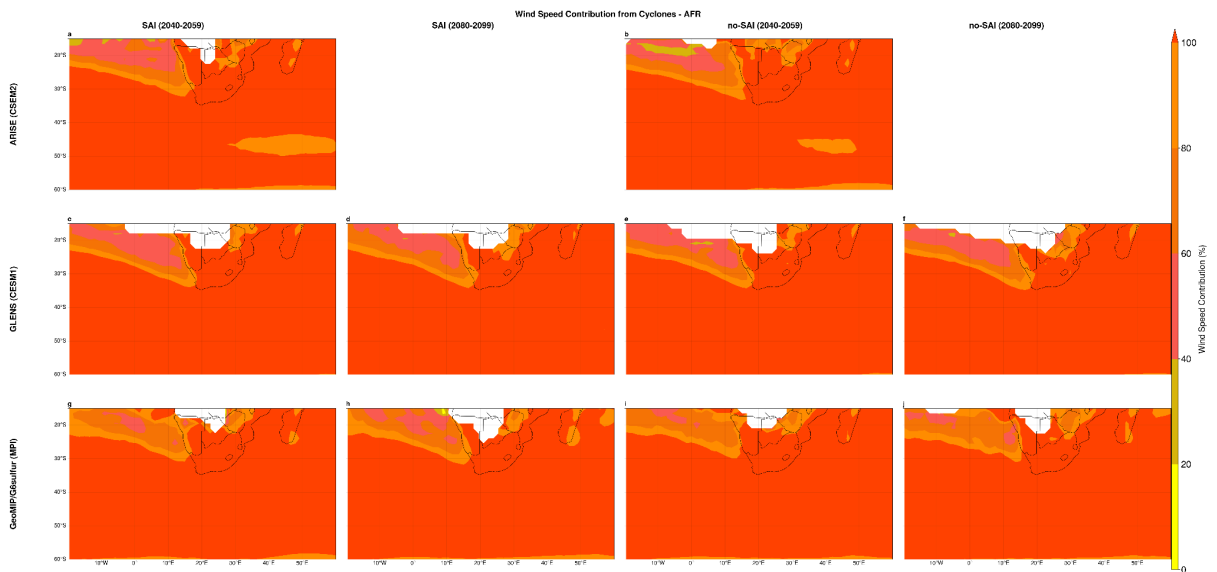


**Figure SM4** Similar to **SM3** but for 10-m wind intensity.

**Figures SM5** and **SM6** show the same fields as the two previous figures, but for the Southern Africa (AFR) region. Greater contributions of cyclone precipitation (**Figure SM5**) in the GLEN and ARISE models, with contributions greater than 20% near Madagascar. As for wind speed contributions (**Figure SM6**), cyclones contribute less to wind intensity near the western edge of AFR (values between 40 and 80%).

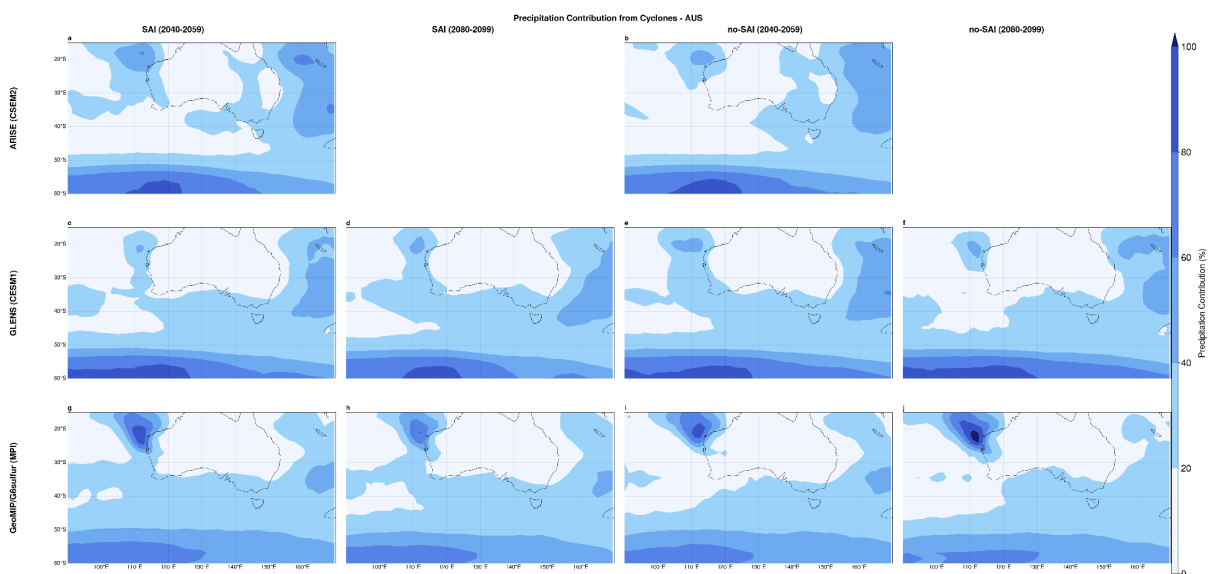


**Figure SM5** Annual relative contribution (%) of extratropical cyclones to the total precipitation under (a, c, f, i, j) SAI and (c, g, h, k, l) no-SAI for the AFR region for the near and far future.

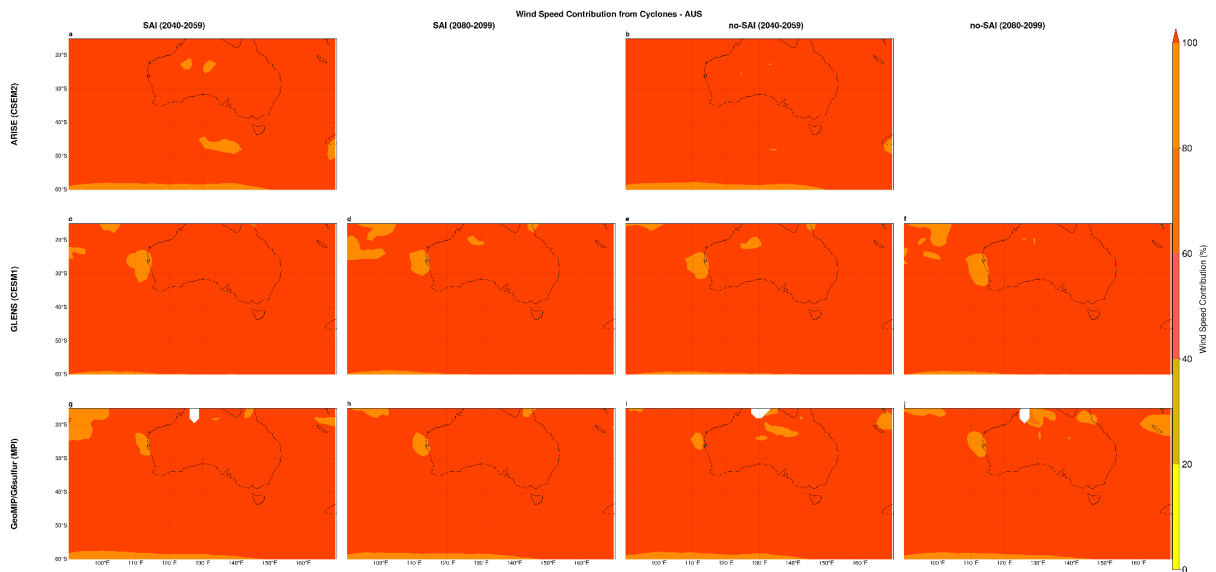


**Figure SM6** Similar to **SM5** but for 10-m wind intensity.

The same is shown for the region of Australia (AUS), where the relative contribution of precipitation (**Figure SM7**) indicates higher values (up to 60%) in the west of the continent under the ARISE and GLENS perspectives and reaching over 100% in GeoMIP/G6Sulfur under the no-SAI experiment in 2080-2099. For wind speed (**Figure SM8**), it is possible to see regions with a lower contribution to extratropical cyclones in the extreme northwestern part of the continent (80-100%), mainly in GeoMIP/G6Sulfur.



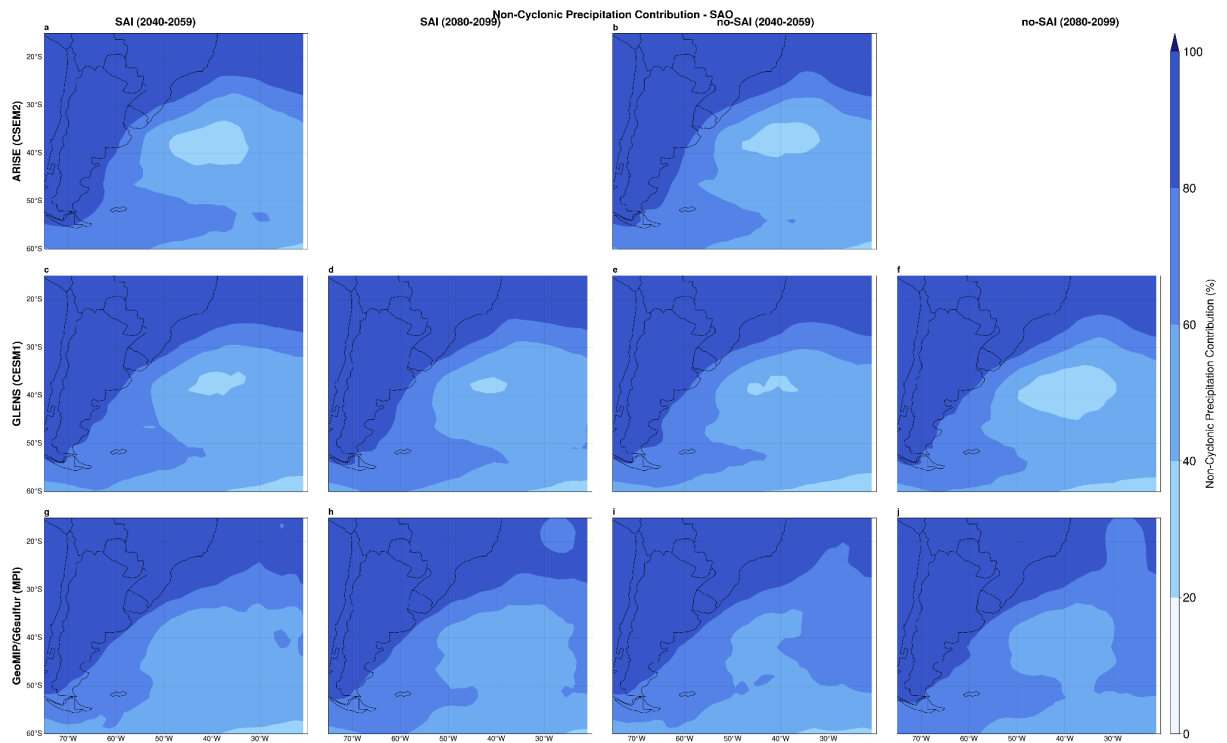
**Figure SM7** Annual relative contribution (%) of extratropical cyclones to the total precipitation under (a, c, f, i, j) SAI and (c, g, h, k, l) no-SAI for the AUS region for the near and far future.



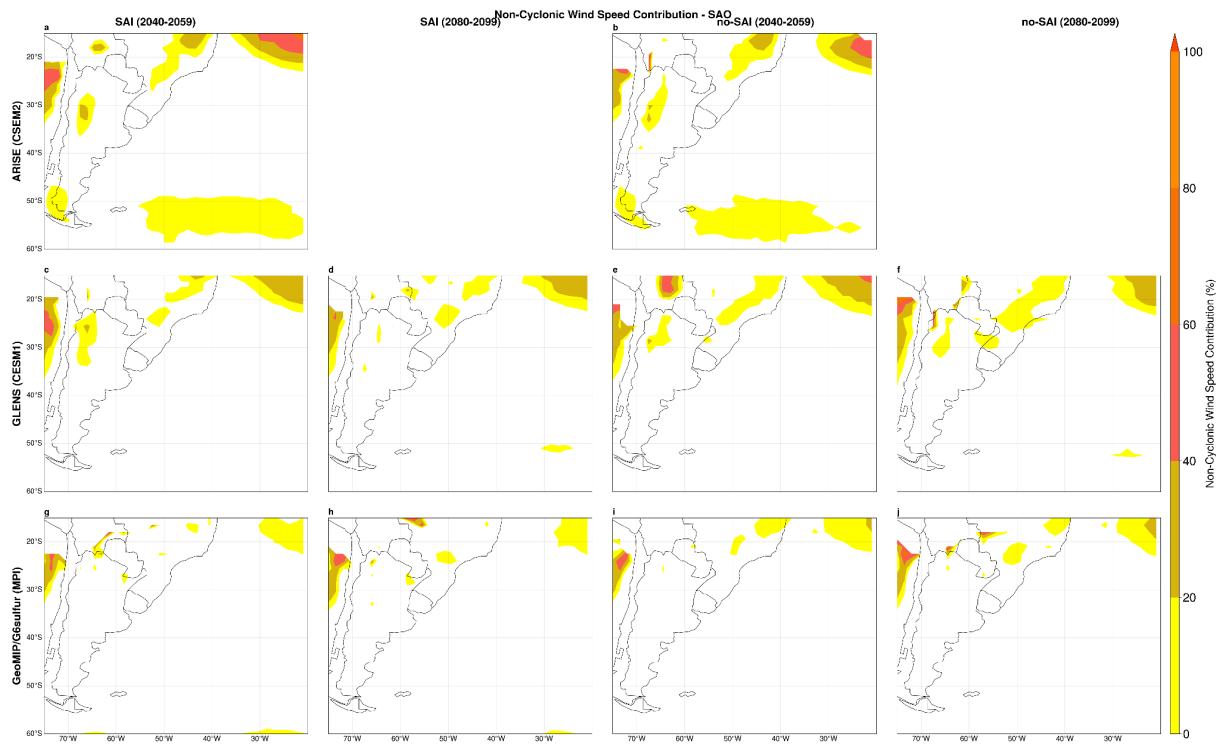
**Figure SM8** Similar to **SM7** but for 10-m wind intensity.

Following the same idea as the figures for the relative contribution of precipitation and wind intensity from extratropical cyclones, the following figures refer to the relative non-cyclonic contribution to precipitation and wind intensity. This means that the amount of these variables related to extratropical cyclones per region was removed from the annual average value. Thus, **Figure SM9** shows that for SAO, the contribution of non-cyclonic precipitation is greater than 80% on the continent, showing that other phenomena can impact the annual precipitation regime. The same behavior is observed in **Figure SM11**, which shows that for the AFR region, the continental portion is mostly (more than 80%) affected by non-cyclonic precipitation. For the AUS region (**Figure SM13**), there are mixed characteristics depending on the model. The GeoMIP/G6Sulfur experiment presents values on the continent between 80-100%, but with a region to the west with a more pronounced cyclonic contribution (between 0 and 20%).

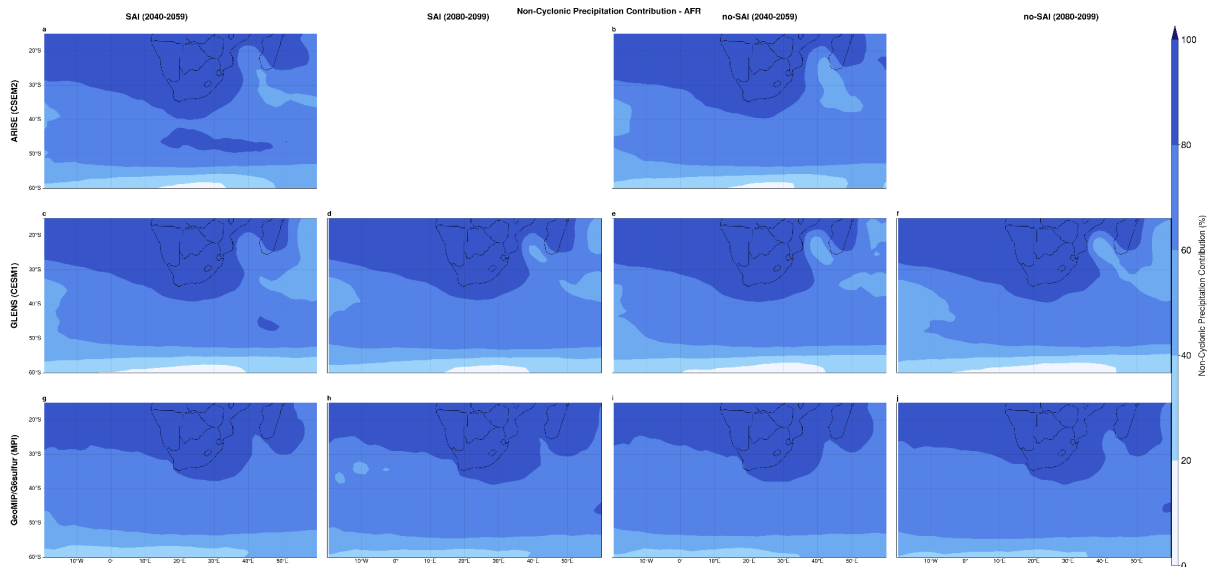
**Figure SM10** shows that for wind speed, there are regions with relatively low non-cyclonic contribution (between 0-20%), mainly in southeastern South America; however, stronger wind intensities are associated with extratropical cyclones. For the AFR region (**Figure SM12**), values are observed in the northwest of the region with the greatest non-cyclonic contribution (between 40 and 60%), but again on the continent it can be seen that extratropical cyclones still play a role in wind intensity (the same occurs for the AUS region, **Figure SM14**).



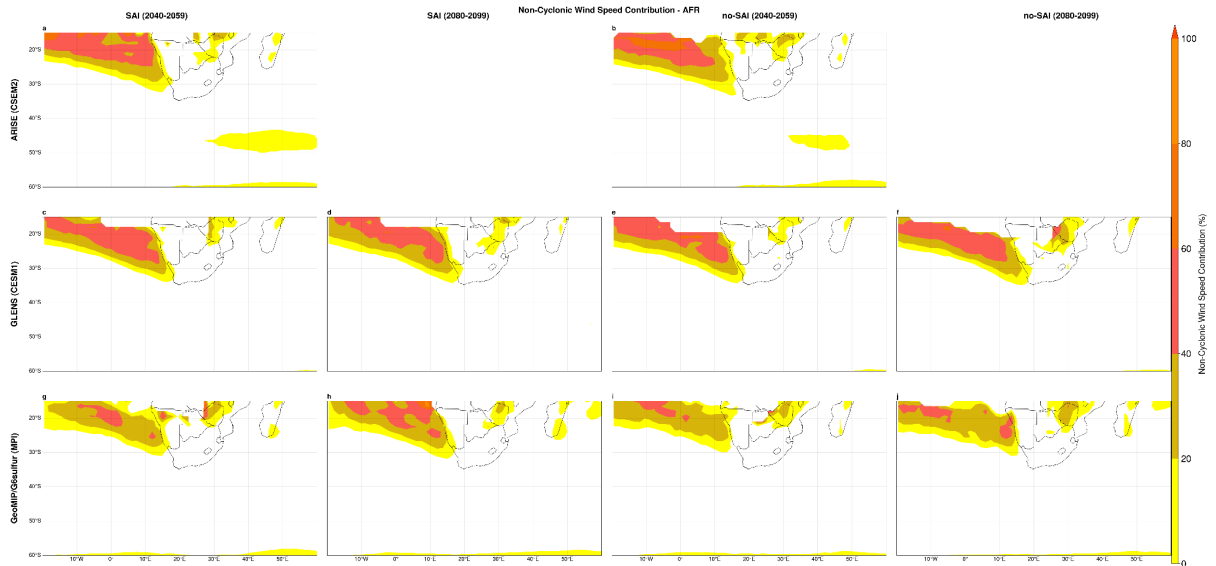
**Figure SM9** Non-extratropical cyclones contribution (%) to the total precipitation under (a, c, f, i, j) SAI and (c, g, h, k, l) no-SAI for the SAO region for the near and far future.



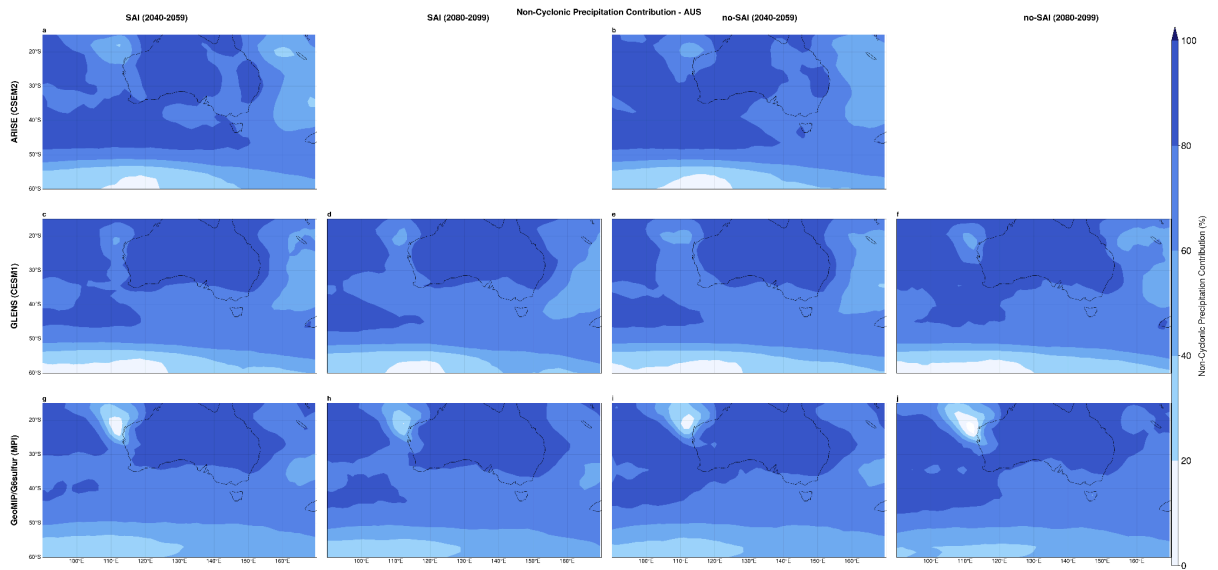
**Figure SM10** Similar to **SM9** but for 10-m wind intensity.



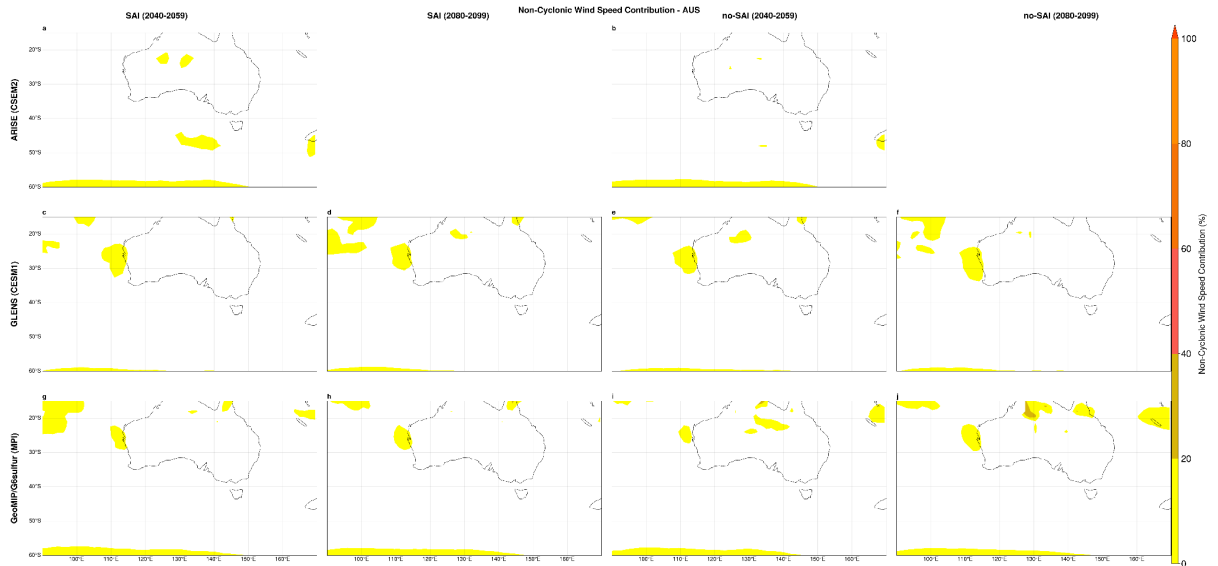
**Figure SM11** Non-extratropical cyclones contribution (%) to the total precipitation under (a, c, f, i, j) SAI and (c, g, h, k, l) no-SAI for the AFR region for the near and far future.



**Figure SM12** Similar to **SM11** but for 10-m wind intensity.

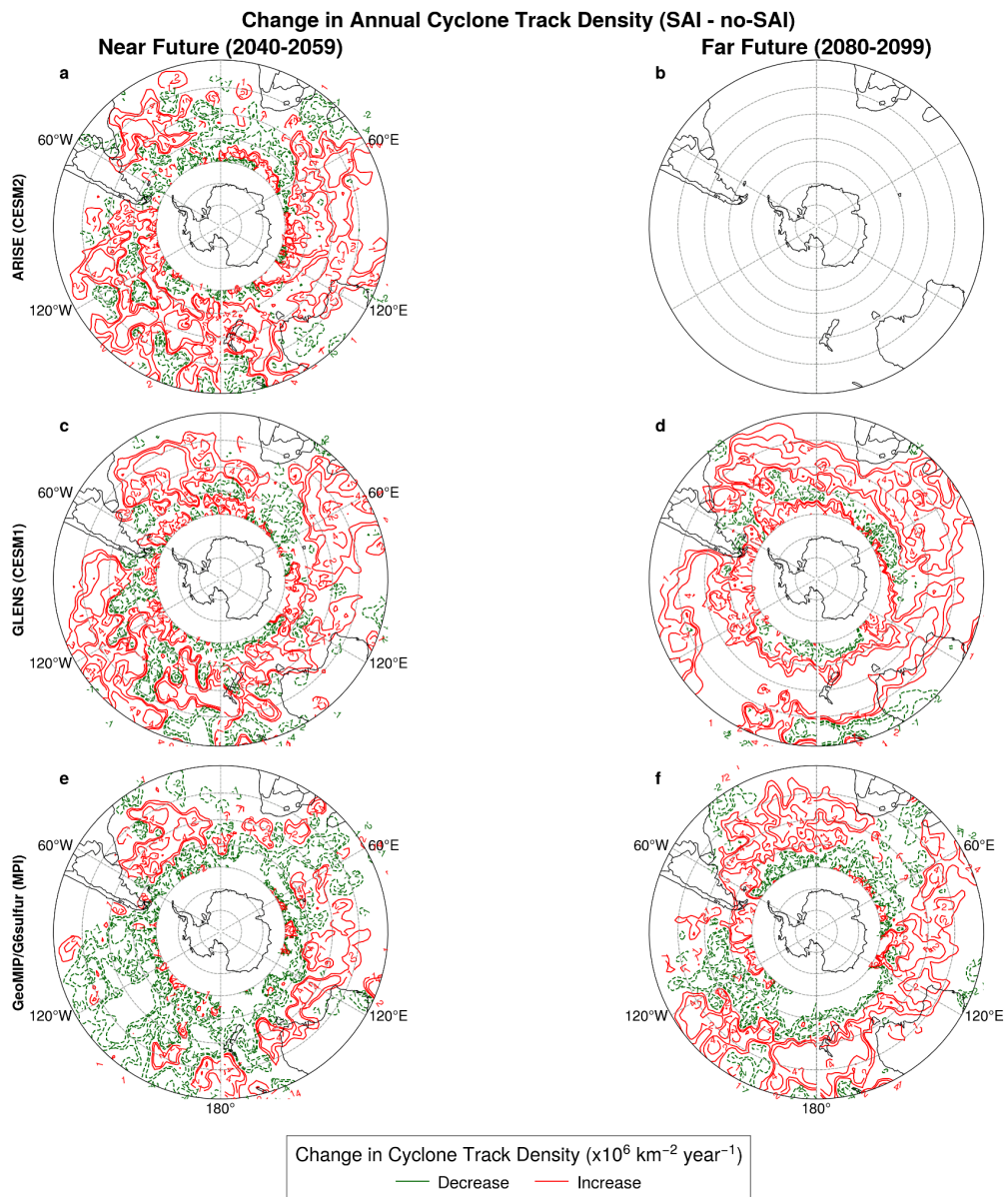


**Figure SM13** Non-extratropical cyclones contribution (%) to the total precipitation under (a, c, f, i, j) SAI and (c, g, h, k, l) no-SAI for the AUS region for the near and far future.



**Figure SM14** Similar to **SM13** but for 10-m wind intensity.

The following shows the statistically significant change under the non-parametric Mann–Whitney U-test (Mann & Whitney, 1947) of the total density of cyclones in the near future (left column) and far future (right column) for each of the projects (**Figure SM15**). Red (green) colors indicate a significant annual increase (decrease).



**Figure SM15** Changes in extratropical cyclone density. Lines show significant increases (red) and decreases (green) in cyclone density.



## 8. CONCLUSIONS

This study evaluated the climatology and characteristics of extratropical cyclones in the Southern Hemisphere from the perspective of climate change and using the SRM approach, more precisely SAI in the future climate. The research sought to fill a significant gap in the scientific literature by investigating the potential impact of this geoengineering technique on the frequency, intensity, trajectory, and precipitation and wind associated with ETCs in vulnerable regions such as Southern Africa, South America, and Australia. These phenomena are projected to increase in intensity due to global warming, making it vital to understand how SAI could influence these climatological aspects.

Furthermore, during the study, a substantial gap was identified in the literature, especially in Brazil, regarding the understanding and visibility of CI among the scientific community. In particular, there was a lack of studies evaluating the impacts of CI in the Global South, highlighting the need for and authenticity of this research. The methodology adopted in this thesis involved the analysis of global climate simulations from projects such as GeoMIP, GLENS, and ARISE-SAI, which apply different radiative forcing scenarios, with and without SAI. The study focused on assessing mean sea level pressure, wind intensity, and precipitation associated with cyclones, considering separately the trends of the historical period and future projections, with an emphasis on the coastal regions of South America, Southern Africa, and Australia, where the impacts of these systems can be particularly severe.

During the SAI preparation of the work, an important gap was identified in the literature related to the fundamental concepts of CI, which motivated the development of the first article of the thesis: a comprehensive review of the basic principles of the area, its different types of interventions, purposes, advantages, and limitations. This article, published in a renowned and prestigious Brazilian journal, provides the conceptual basis necessary for the subsequent studies conducted in this research.

### 8.1 Climate Intervention Techniques

The review conducted in the first phase of this thesis clarified that CI covers a broad spectrum of technological strategies designed to deliberately manipulate the planetary environment. These are mainly categorized into SRM and CDR. SRM techniques, such as SAI and MCB, aim to reflect a small percentage of sunlight back into space to rapidly cool the planet. SAI mimics the cooling effect of volcanic eruptions by injecting sulfate aerosols into the stratosphere, while MCB seeks to increase the reflectivity of low-level marine clouds by seeding them with sea salt particles. On the other hand, CDR approaches focus on addressing the root cause of climate change by extracting CO<sub>2</sub> from the atmosphere. They range from nature-based solutions, such as reforestation and ocean fertilization, to technological methods such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DACCS). The review highlighted that while these technologies offer



potential pathways to help the mitigation, they carry significant risks and uncertainties, including potential termination shocks, regional climate disparities, and complex ethical and governance challenges.

## 8.2 Climatology of ETCs

Regarding the behavior of extratropical cyclones in the Southern Hemisphere, the results obtained from the analysis of the ARISE, GLENS, and GeoMIP/G6sulfur projects indicate consistent trends among the different models. Both SAI and no-SAI scenarios project a decrease in the annual frequency of ETCs at the end of the century (2080-2099). For instance, while statistically significant negative trends in cyclone frequency were observed for most no-SAI projections, the ARISE-SAI and GLENS-SAI ensembles did not exhibit statistically significant trends, suggesting that SAI intervention effectively dampens the decline in cyclone numbers expected under global warming.

A critical finding concerns cyclone intensity: under no-SAI warming scenarios, cyclones are projected to become deeper and more intense. Specifically, the GeoMIP<sub>SSP5-8.5</sub> scenario indicates that cyclones at the end of the century may be 3.1 hPa and 4.0 hPa stronger in terms of initial pressure and minimum pressure, respectively, compared to the current climate. On the other hand, in scenarios with SAI, the intensity of these systems remains closer to the reference period (2015-2024). In all analyzed future timeslices, cyclones were found to be statistically significantly weaker (i.e., higher central pressure) under SAI compared to no-SAI scenarios.

Other lifecycle characteristics showed minor changes when SRM was used; traveling distances remained within the 3000–3300 km range, with mean differences of only ~300 km (10%) between scenarios, lifetime reductions did not exceed ~4 hours (approximately 4% of the total duration), and average speed had a reduction of 0.5 ms<sup>-1</sup>. Spatially, both scenarios exhibit a poleward shift of ETCs trajectories, with decreased density in mid-latitudes and an increase around Antarctica, although SAI scenarios generally present a higher track density than no-SAI.

## 8.3 Precipitation and Winds associated with ETCs

To complement the previous analyses, the analyses were extended to precipitation and 10-m wind intensity specifically associated with ETCs in subdomains, including the southwestern South Atlantic Ocean (SAO), Southern Africa (AFR), and Australia (AUS). The comparison between SAI and non-SAI scenarios revealed that SAI generally leads to a weakening of both precipitation and near-surface wind intensity associated with cyclones. In the near future (2040–2059), the analysis of ARISE and GLENS ensembles showed sharp decreases in cyclone-associated precipitation of up to 80% over specific continental regions,



including southeastern South America, Western Australia, and eastern South Africa. Regarding wind intensity, the projections indicated a general weakening pattern south of the subtropics and over continental areas, with statistically significant reductions of up to  $2 \text{ ms}^{-1}$  under SAI scenarios compared to no-SAI.

Furthermore, the contribution of cyclones to total annual precipitation and wind intensity is expected to decrease from the near future to the distant future under SAI conditions, particularly in GLENS simulations. For the SAO region specifically, the results indicated a mixed signal in the near future but a predominant decrease in the cyclonic contribution to total precipitation by the end of the century. Composite analyses of the most intense cyclones further corroborated these findings, showing that while initiatives such as GLENS project coherent spatial patterns of suppressed cyclonic intensity (higher pressure, weaker winds, and reduced rain cores), others such as GeoMIP exhibit greater spatial variability. Ultimately, the data suggest that the SAI acts to mitigate the extreme cyclone characteristics expected under unmitigated warming.

#### 8.4 Final Remarks

The conclusions of this doctoral thesis emphasize that, although aerosol injection into the stratosphere has the potential to compensate for some of the dynamic and thermodynamic changes in extratropical cyclones caused by global warming, it is not a simple return to a historical climate state. There is an urgent need for further studies addressing this issue. A growing number of studies address the fact that different SAI strategies are accompanied by different responses from the climate system ([Zhao et al. 2025](#)). There is also growing interest in other intervention methods, such as MCB ([Hirasawa et al. 2025](#)). Thus, there is a need for studies that not only address other methods/strategies, but also involve larger numbers of GCMs and use high-resolution regional modeling to better capture localized impacts, particularly in coastal areas vulnerable to storms and extreme wind events, as well as include uncertainties related to different model representations.

It is also important to mention the methodological limitations of this study. The analysis was based on individual climate models for each intervention initiative (CESM1, CESM2, and Max Plank Institute-ESM - MPI-ESM), which subjects the results to structural biases and specific parameterizations for each model, failing to capture the full uncertainty that a broader multi-model ensemble would provide. It is worth noting that the choice of the three initiatives sought to understand how ETCs respond to each strategy, analyzing them individually rather than strictly comparing their outputs. Additionally, the availability of only three members per ensemble restricts the statistical robustness necessary to fully assess the natural internal variability of the climate system in response to SAI forcing. Regarding the capture of systems, although the tracking algorithm used is widely validated in the literature, it is sensitive to the spatial resolution of the interpolated data.



Finally, the filters applied (such as the exclusion of thermal lows based on fixed geographic masks and the minimum lifetime threshold) although essential for isolating transient extratropical cyclones, may have excluded hybrid systems or complex cyclogenesis occurring at the margins of these definitions. Future research should also evaluate other critical components of the Earth system, such as the interaction between the SAI and extreme weather events and composite events, assessing impacts holistically rather than in isolation. It would be interesting to conduct these assessments using a broader set of models, as well as different strategies, such as the MCB.

Significant challenges remain, particularly regarding the side effects of these interventions on regional precipitation patterns and the lack of robust international governance. Implementing such technologies without global consensus poses serious geopolitical risks. Solutions must involve establishing transparent and inclusive regulatory frameworks that ensure equitable decision-making. In the Brazilian context, and for the Global South in general, it is imperative to move from a position of passive observation to active participation in CI research. Developing local expertise and promoting scientific debate in Brazil it is crucial to ensure that the country's specific vulnerabilities (such as food security and water resources) are considered in any future global deployment of climate intervention technologies.



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