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Review the past for
planning the future

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Atmosphere-Climate Dynamics, Variability, and
Predictability

A Special Message from WCRP

At the publication of this edition of the CLIVAR Exchanges, the WCRP Joint Scientific Committee Chair, Timothy Naish, and myself as the Head of the WCRP Secretariat, are visiting our International CLIVAR Project Office (ICPO) and ICPO's hosts, the Ocean University of China (OUC) and Lao-Shan National Laboratory (LSNL). In particular, we are very happy that we will be there at the occasion of the anniversary celebrations: the 102nd anniversary of OUC and the 80th anniversary of OUC's multi-disciplinary marine studies with three Colleges including the College of Oceanic and Atmospheric Sciences (COAS). We congratulate our OUC colleagues for their success in ocean and climate education and research, including being ranked as the first in Marine Science in the 2026 Global Ranking of Academic Subjects by ShanghaiRanking, officially known as the Academic Ranking of World Universities (ARWU)— a highly influential annual publication that evaluates and ranks higher education institutions globally. We are proud that WCRP's core project CLIVAR's international project office is located in such a prestigious campus. We are also grateful to ICPO's other co-host, the Lao-Shan National Laboratory (LSNL), with many highly respected international ocean and climate scientists (e.g. on ENSO research) who are actively involved in and support CLIVAR activities. Together with WCRP's other eleven International Project Offices, ICPO plays a critical role in carrying out WCRP's mission and goals.

The periodical magazine CLIVAR Exchanges is an effective way for climate scientists to exchange research results and ideas freely and in a timely manner. We encourage our community to read articles featured in the Exchanges, contribute articles to it, and engage in research discussions. The review articles featured in this edition, together with others, will serve as foundational materials for CLIVAR and WCRP in formulating their next strategic science and implementation plans.

We wish everyone continued success in CLIVAR research and its applications to society, as the world faces more extreme and ever changing climate events.

Timothy Naish
Chair, WCRP Joint Scientific Committee

Michael Sparrow
Head, WCRP Secretariat



Editor's message

I am greatly honored and excited to serve as the new ICPO Director, and to work with the CLIVAR community and its partners to realize the CLIVAR's mission goals and objectives. Understanding the variability of the ocean and climate systems to address its worldwide impact on society requires integrated use of observations, modeling, analysis and synthesis, and communication and engagement with stakeholders and the public.

Research on ocean and climate changes and their impacts to society is now more important than ever, as the world faces accelerated and amplified climate extreme events with the global climate warming up. The [2023-2024 rapid record-setting ocean warming](#) and marine heatwaves caught both the public and scientists out of guard and preparation, and it was thought as an anomaly event rather than normal, [but now in 2026 the ocean surface temperature started once again to break the record set in 2023-2024](#), and the world is facing a potential "super" charged [El Nino event in 2026-2027](#). There is an urgency for the CLIVAR and other climate research communities to understand these events for better predictions and society preparedness. I [myself have](#) been in the front rows experiencing these changes and their disastrous impacts (figures below), thus myself, and the public in general, will benefit from, and be grateful to, your research discoveries and their societal applications! This is my passion.

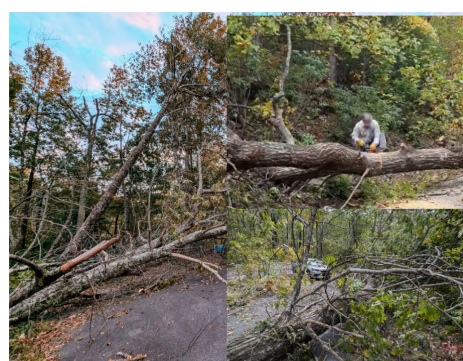
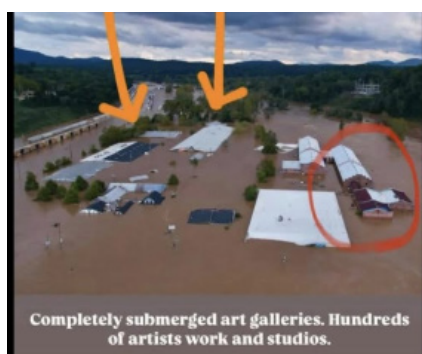


Figure Caption: The 2025 Hurricane Helene caused far-reaching (in both geographical area and impact) and devastating damages to many US eastern States including John's hometown areas and his own home, with more than 250 deaths, \$79 Billion economy losses, and washed away villages. The right picture shows John was chainsawing downed trees on this homesite, which barely missed his house.

CLIVAR entered 2026 by introducing [a new CLIVAR logo](#), responding to the new WCRP branding and in reflection of 30 years of CLIVAR history and achievements. As we chart our course for the next decade, we embrace a new chapter with renewed energy and a cohesive vision. Aligned with the new WCRP visual identity, the new CLIVAR logo features a color palette inspired by Earth's key systems: blue ocean, cyan ice, yellow atmosphere, and green land. Its stylized lines, symbolizing the waves of a dynamic ocean and atmosphere, encircle the WCRP's emblem, representing our unified purpose: to advance understanding and predicting the climate system, foster global scientific collaboration, and strengthen our commitment to bridging science and society. Please reflect on these as we start to plan our activities and events moving forward.



In mid 2026, CLIVAR has also approved two Research Focus (RF) projects: the [Ocean oxygen to Carbon Heat Nexus in a Warming Climate \(O2CH\)](#), and the [Confronting Earth System Model Trends and Multidecadal Variability with Observations \(CEMT-MV\)](#). The O2CH project will investigate the intertwined dynamics of oceanic heat and the cycling of carbon and oxygen under the pressure of accelerating anthropogenic warming, with ocean oxygen as the central element. The main goal of the CEMT-MV project is to focus international research on identifying and predicting external-forced trends and internally-generated MDV, thereby providing a more informed assessment of projections for the coming decades.

Looking ahead, two major activities for CLIVAR are organizing a decadal CLIVAR Open Science Conference (OSC) and creating a new strategic Science Plan. These two activities will dove-tail with each other, as well as dove-tail with the WCRP's new science plan. The Pan-CLIVAR Meeting in 2014, followed by the CLIVAR Open Science Conference (OSC) in 2016, laid the foundation for the development of the current decadal CLIVAR science plan (2018-2028). About a decade later, the Pan-CLIVAR Meeting in 2025, followed by a planned CLIVAR OSC for late 2027, will be once again critical for creating the next decadal CLIVAR Science Plan. Involvement and contribution from the community are critical for the success of all of the above, and details will be sent to the community when available.

CLIVAR researches cover a wide range of scales and methodologies, from micro ocean mixing and diffusion process, boundary currents and upwelling, turbulent air-sea interactions, meso scales eddies, ocean basin wide circulations, to inter-ocean connections and teleconnections over oceans and land, and from observations to data analyses and modeling. **This edition of the CLIVAR Exchanges (85) collects some articles reflecting the complexity of the ocean-climate systems, and reflects achievements by some CLIVAR Panels and Research Foci (RF), based on results from the 2025 Pan-CLIVAR meeting.**

The **Pacific Regional Panel (PRP)** article by *Taschetto et al.*, ***"CLIVAR contribution to ENSO understanding"***, summarizes advancements in several interconnected areas: improving understanding of ENSO dynamics and predictability, refining theoretical frameworks, characterising decadal modulation of ENSO, advancing knowledge of atmospheric teleconnections in present and future climate, and strengthening links between Pacific physical variability and impacts on biogeochemical processes. Readers are encouraged to review their achievements and utilize their open-source oriented analysis tools.

The article ***"The CLIVAR Research Focus (RF) on Tropical Basin Interaction (TBI): Achievements and Legacy"*** by *Richter et al.* describes the motivation and aims of this RF, summarizes its activities and achievements, and discusses its legacy and future perspectives for TBI research. One of the main goals of the RF TBI was to establish an experiment design that would be followed by all models, to reveal systematic model errors. Other efforts include making paleo proxy data more accessible, clarifying the requirements for observation networks to address TBI, providing the community with conceptual models and statistical tools for the study of TBI, and capacity building through workshops, summer schools, and coordinated research activities.

The article ***"The Southern Ocean Region Panel (SORP): Advancing Antarctic Science through International Coordination and Collaboration"*** by *Prend et al.* summarizes SORP's activities and achievements. SORP is co-sponsored by WCRP CLIVAR and Climate and Cryosphere Project (CliC) together with the Scientific Committee on Antarctic Research (SCAR) of the International Science Council (ISC). SORP brings together experts in observations and modelling to synthesize recent advancements in Antarctic science, identify major knowledge gaps, and outline research priorities, through organizing workshops, webinars, and summer schools. SORP played a central role in the inception of the Southern Ocean Freshwater Input from Antarctica (SOFIA) initiative, which is an international modelling effort to quantify the climate response to Antarctic meltwater and associated uncertainties. Looking ahead, a major SORP focus is supporting the implementation of Antarctica InSync, a UN Ocean Decade Programme that aims to synchronize observational efforts across Antarctica and the Southern Ocean from 2027-2030. This once again demonstrates the importance of cross organization efforts to achieve a bigger goal, and the community is encouraged to participate.

The ocean blue economy is vital in driving global economic growth and ensuring food and job security for people. Coastal winds and upwelling, and their changes, are critical physical processes that impact the marine ecosystems. The article ***"Winds of Change: two-decades of change in the four major Eastern Boundary Upwelling Systems"*** by *Veitch et al.* summarizes the changes over the last two decades of the world's four major eastern boundary upwelling systems along eastern margins of the Atlantic and Pacific ocean basins. I would like to point out that future studies are needed to understand the uncertainties associated with these change signals, in particular to address biases associated with satellite observations and models, partly due to the high spatiotemporal variabilities and the lack of in-situ/ground-truth observations. The two following papers below exemplify the uncertainties in modeling, datasets, and analyses.

Evaluation and validation of widely used reanalyses are important as well to diagnose the true change signals. The article by *Bourdallé-Badie et al.*, ***"MER-EP initiative: the Marine Environment Reanalyses Evaluation Project"*** describes an international effort to assess the quality, consistency, and associated uncertainties of ocean reanalyses. Building on the legacy of earlier intercomparison projects, MER-EP expands the scope of evaluation beyond physical oceanography to include sea ice, ocean waves, and marine biogeochemistry, while placing user-oriented applications at the centre of the assessment strategy. Both reanalysis/dataset developers and their users

are strongly encouraged to participate in this initiative. MER-EP is a GSOP endorsed project, and the community is encouraged to participate.

The research article ***“Uncertainties in Precipitation Datasets across Different Timescales: The Case of South America”*** by Reboita *et al.* demonstrates that uncertainties among the most widely used precipitation datasets over South America are not limited to absolute rainfall amounts but also affect the representation of the annual cycle, long-term trends, seasonal variability, and sub-daily characteristics. Conclusions regarding precipitation variability and change may depend substantially on the dataset selected. This article reflects a common theme that has been revealed by a number of CLIVAR efforts: the continued need for better observational data.

Addressing global warming by the so-called "Geoengineering" is understandably highly controversial, as it has tremendous real-life and geopolitical implications. Its impacts need to be fully understood before any large scale implementation. The article ***“Southern Hemisphere Extratropical Cyclone Response to Solar Radiation Modification Techniques: Marine Cloud Brightening and Stratospheric Aerosol Injection”*** by Rebeiro *et al.* contributes to this knowledge base by analyzing model simulation results in terms of Southern Hemisphere extratropical cyclone responses.

I fully enjoyed reading the above articles while editing this issue of the CLIVAR Exchanges, from which I learned a lot of the CLIVAR activities which were beyond the reach of my normal past work at NOAA. I look forward to engaging with the CLIVAR community in-person in the months and years to come.

Call for articles on ENSO and Ocean and Climate Extremes for the next issue of CLIVAR Exchanges, #86: With the anticipation of an oncoming “super” El Nino and its profound impact, we call for review and new research and discussion articles on ocean and climate extremes and their impacts to society for the next issue of the CLIVAR Exchanges. Please submit yours by 31 January 2027, and the earlier the better. We will review the articles once we receive them, and publish an edition once a critical number is reached.

Last but not the least, I thank many people for getting me on track quickly here: the CLIVAR SSG chairs, WCRP Secretariat and Hindumathi who actively supported ICPO during the months when the ICPO Director position was vacant. We are indebted to the ICPO team members, Joana Gonzalez, Di Zhang, and Yang Zhao, who took on extra tasks to keep ICPO running in the five months before my arrival, and for offering their insights. Their work proficiency reflects the legacy of Dr. Agus Santoso, the past and inaugural Director when ICPO was moved to the new host, the Ocean University of China/Laoshan National Laboratory (OUC/LSNL). Finally but most importantly, I give my sincere thanks to ICPO's host, OUC/LSNL, particularly Dr. Xiaopei Lin, for their support for ICPO, and their care and assistance to me and my wife to settle down in this beautiful coastal city of Qingdao. We fully enjoyed our after-dinner walks along the coastlines, and our goal is to eventually put our footprints over all the walkable sections along the coast.

Ocean-climate change and its impacts have no boundaries and are worldwide scientific, societal, and humanity issues. United and leveraging each other's expertise and resources, we can achieve more towards bigger goals! I will do my best to lead the ICPO team in facilitating CLIVAR activities to achieve its objectives.



John Huai-Min Zhang
Director, International CLIVAR Project Office

CLIVAR Exchanges 85 is edited by the ICPO Team: John Huai-Min Zhang, Joana Gonzalez, Di Zhang, Yang Zhao, and Abiola John Osanyintuyi (student intern). Assistance from the CLIVAR SSG Co-Chairs are greatly appreciated. We thank all the authors who contributed papers to this issue. We appreciate the resources provided by the ICPO host - the Ocean University of China and Laoshan National Laboratory.

The CLIVAR Scientific Steering Group leadership team members are:

Dr. Gokhan Danabasoglu, Co-Chair

Dr. Francois Engelbrecht, Co-Chair

Dr. Mathew Collins, incoming Co-Chair

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The Pacific Ocean covers about 30% of the global ocean, playing a central role in the Earth's climate system. Year-to-year variations in the Pacific sea surface temperature expressed through El Niño–Southern Oscillation (ENSO) affect global mean temperatures, accelerating or slowing global temperature rise, modulate monsoons, and shape weather and climate patterns, influencing extremes such as droughts, floods, and heatwaves worldwide. On longer timescales, decadal variability in the Pacific contributes to shifts in climate patterns that impact ecosystems, sea level, and regional climate risks.

Despite decades of progress, key processes governing Pacific variability, their impact on climate, and their response to a warming world are not fully understood and continue to be an area of active research. Improving ENSO prediction requires sustained observations, advances in modelling, and strong international coordination. Over the past decade, the CLIVAR Pacific Region Panel (PRP) has worked with other CLIVAR Panels and Research Focus Groups and the international community, enabling progress in ENSO theory, observations, modelling, and impacts, helping advance understanding of the Pacific climate system.

Many CLIVAR scientists have contributed to a growing body of literature on Pacific climate and ENSO, including major synthesis efforts such as the book *“El Niño Southern Oscillation in a Changing Climate”* edited by McPhaden, Santoso, and Cai (McPhaden et al. 2021). This article highlights selected current and past CLIVAR activities, led by and in collaboration with the PRP, that have contributed to recent advances in ENSO understanding.

PRP activities have contributed to advances in several interconnected areas: improving understanding of ENSO dynamics and predictability; refining theoretical frameworks; characterizing decadal modulation

of ENSO; advancing knowledge of atmospheric teleconnections in present and future climate; and strengthening links between Pacific physical variability and impacts on biogeochemical processes. The PRP, together with other panels, worked toward engaging the community around these important issues and toward capacity building, training students and early career researchers.

Advancing ENSO dynamics, theory, and models

The **ENSO Conceptual Model Working Group** created in 2020 has helped clarify the fundamental processes that conceptual models must capture to represent ENSO behavior and characteristics, thus strengthening the theoretical basis for interpreting ENSO dynamics and predictability. The group produced a comprehensive review synthesizing current knowledge on ENSO conceptual models, bringing together classical frameworks (including the delayed oscillator, western Pacific oscillator, and advective–reflective oscillator) under a unified perspective, with a focus on the Recharge Oscillator (RO) model (Vialard et al 2025). Specifically, the study demonstrates that the RO model explains most ENSO properties and can be extended to represent diversity by including additional variables. It also proposes avenues for using the RO to understand ENSO interactions with other modes of variability and its behavior in a changing climate. The group is currently developing an accessible Python implementation of the Recharge Oscillator model to support broader community use and education.

Complementing this, the **ENSO Metrics Working Group** (established in 2020) has addressed a long-standing challenge in the field: the lack of consistent diagnostics for evaluating ENSO in climate models. The group coordinated an international effort to develop a standardized set of diagnostics for evaluating ENSO characteristics in climate models. This work has resulted in an open-source Python package (via GitHub

repository and incorporated into the PCMDI Metrics Package) that enables consistent assessment of ENSO characteristics, teleconnections, and processes across simulations, including estimating uncertainties for CMIP5 and CMIP6 models (Planton et al. 2021, 2024). The package is currently available to the community for use. Further efforts are in progress to integrate the package into community tools such as the ESMValTool (<https://esmvaltool.org/>), with application and benchmarking occurring in Australia, France, and Germany, via ACCESS-NRI, IPSL, and MPI Institute, aiming to expand applications to evaluate the upcoming CMIP7 model outputs.

Understanding ENSO modulation and Pacific variability across timescales

The PRP has also been very active in pursuing understanding of Pacific variability at timescales longer than the ENSO timescale. Two workshops, the first at Centro Nacional de Acuicultura e Investigaciones Marinas (CENAIM) and Escuela Superior Politécnica del Litoral (ESPOL) in Ecuador and the second at LOCEAN-IPSL, Sorbonne University in Paris, were organized to discuss decadal climate variability in the tropical Pacific, leading to a review and perspective article on the nature of Tropical Pacific Decadal Variability (TPDV) in the context of climate change (Power et al. 2021). To further explore internal climate variability at timescales longer than typical ENSO timescales, the PRP created the **Tropical Pacific Decadal Variability Working Group** (2021–2024), which provided a major synthesis of variability in the Pacific Ocean on multi-decadal timescales. A review paper described the mechanisms of TPDV, including Rossby wave-driven adjustments, changes in upper-ocean overturning circulation, and subsurface spiciness anomalies, as well as atmospheric drivers such as midlatitude variability and inter-basin teleconnections (Capotondi et al. 2023). Through the review paper, the TPDV working group clarified existing processes and identified key uncertainties in this topic, providing a framework for interpreting TPDV and setting priorities for future research.

Through collaboration with CLIVAR-endorsed projects such as SPICE and NPOCE, the PRP has advanced understanding of the connections between the subtropical and tropical Pacific (Ganachaud et al. 2014; Wang et al. 2018). These efforts have helped identify the pathways through which subtropical waters supply the equatorial region and have improved characterization of the variability of low-latitude western boundary currents (LLWBCs), which play a key role in the recharge–discharge processes governing ENSO and potentially the TPDV.

The PRP is also contributing to the CLIVAR TROPICS Working Group, a joint group between CLIVAR

Climate Dynamics Panel, CLIVAR PRP, and WCRP CFMIP, aimed at elucidating the mechanisms behind the formation of tropical SST warming patterns across the past, present, and future (Watanabe et al. 2024). This issue is fundamental to better understand how ENSO will evolve in a future climate, a scientific question that remains unanswered.

Advancing ENSO impacts on climate and biogeochemistry

Two working groups launched in 2024 are addressing emerging priorities on the impacts of ENSO on climate and biogeochemistry.

The **Pacific Atmospheric Teleconnections (PATAC) Working Group** is focusing on how ENSO influences weather and climate globally. While the impacts of ENSO-related teleconnections are well documented, important gaps remain in understanding the mechanisms that drive regional extremes, impacts on the ground, and how these may change in a warmer world. The PATAC working group is working to synthesize current understanding of the mechanisms driving tropical Pacific teleconnections, assessing their representation in climate models, and identifying gaps relevant to societal impacts such as extreme events.

ENSO's influence extends beyond physical climate into marine ecosystems and biogeochemical cycles. The **Tropical Pacific Biogeochemistry–Physical Interactions (BGC-PI) Working Group** aims at advancing research on the two-way coupling between ocean biogeochemical cycles and physical climate processes. Its central focus is on understanding how climate variability shapes ocean biogeochemistry, and how, in turn, biogeochemical processes influence circulation and climate. Key aims of the BGC-PI WG are to identify research gaps in our understanding of these interactions in the tropical Pacific - across both observations and modeling -and to clarify current challenges, needs, and research priorities. The WG also aims to highlight opportunities to address these gaps through coordinated modeling experiments, sustained observing systems, and targeted process studies. In addition, it promotes collaboration and knowledge exchange within the community through seminars, discussions, conference sessions, and the development of a synthesis paper.

Supporting the observing system

Sustained observations of the tropical Pacific are fundamental to understanding and forecasting ENSO and associated climate variability. Over the past decade, the PRP has played an active role in supporting the global observing system and interacting with the Tropical Pacific Observing System (TPOS), to ensure that the needs of the

CLIVAR research community would be fulfilled. The panel has been particularly active during the transition to the implementation phase of the TPOS-2020 design (Kessler and Cravatte 2021). Through engagement with international groups such as the Ocean Observations Panel for Climate (OOPC), the Global Ocean Observing System (GOOS), and the Global Climate Observing System (GCOS), PRP has been a key player to support TPOS implementation and ensuring that observational priorities in the Pacific are aligned with international scientific needs. In addition, the PRP contributed to a community paper on the needs for a pantropical observing system, led by the CLIVAR Tropical Basin Interaction Research Focus (Foltz et al., 2025). The goal was to provide a broader perspective covering the tropical observing system as a whole. Common gaps, needs, and recommendations were identified, and interbasin differences driven by socioeconomic disparities were discussed. Recommendations for improved observations of tropical basin interactions, through oceanic and atmospheric pathways, were presented, emphasizing the benefits that can be achieved through closer interbasin coordination and international partnerships.

While progress has been made over the past decades in improving and continuing the observing system, significant challenges remain. While many of the TPOS2020 recommendations are being implemented, the lack of international agreement to commit to sustain the TPOS poses risks to the long-term sustainability of the system, including gaps in moored observations in the western Pacific, limited expansion of Argo coverage in the tropics, and reliance on contributions from a small number of countries to deploy monitoring equipment. The PRP has worked to raise awareness of these issues within the scientific community (Cravatte et al. 2026) and at major CLIVAR meetings, while continuing to engage with TPOS and partner organizations to strengthen observing capacity in the region.

Enabling knowledge exchange and the next generation of ENSO scientists

Scientific advances in ENSO research have also been driven by strong community engagement. The PRP has organized workshops, summer and winter schools providing training opportunities and supporting the next generation of scientists in this area. In July 2022, a Summer School on “*Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Tropical Oceans, ENSO and their teleconnections*” was co-organized in hybrid format by PRP members and local scientists at the International Centre for Theoretical Physics in Trieste, Italy, attracting over 100 students registered from countries on all six continents. A more recent highlight was the ‘2025 Wyrutki Symposium, “*El Niño–Southern Oscillation:*

Past, Present, and Future”, held in Hawaii, along with the ‘*ENSO Winter School*’, and organized jointly with other CLIVAR Research Foci. These events brought together over 130 scientists across career stages and over 25 students from related disciplines, combining scientific exchange with training and mentorship, and exemplifying the PRP’s commitment to community building.

In 2026, the PRP launched a new **ENSO Webinar Series** (available online) to further expand access to expertise to the scientific community, stakeholders, government, and the public, and to foster ongoing dialogue within the community. The first four webinars featured Jérôme Vialard on the history and development of ENSO theory, Mike McPhaden on the successes and setbacks in development of the ENSO observing system, Michelle L’Heureux on operational ENSO forecasting, and Nicola Maher on the use of large ensemble for ENSO research.

The Panel has also contributed to the organization of conference sessions, and coordinated publications and special collections. A Special Collection on ‘**ENSO Atypical Decade**’ has been organized jointly with the SSG and other CLIVAR panels across the American Meteorological Society journals to explore the unusual variability and evolution of ENSO over the 2014-2024 decade, including the underlying processes and atmosphere-ocean teleconnections, impact on the physical-biogeochemical system, and predictability and prediction in a changing climate.

Looking forward

In summary, the CLIVAR PRP has supported substantial advances towards understanding ENSO dynamics and predictability through theoretical and modelling frameworks, advancing knowledge of ENSO dynamics, low-frequency modulation and local and remote impacts, mediated by atmospheric teleconnections, over land, oceans and biogeochemistry. As the climate continues to warm, understanding how ENSO will change, and how its impacts will evolve, remains a central challenge for climate science. Continued advances will depend not only on new ideas and tools, but also on sustained international collaboration.

Looking ahead, the PRP will continue to support ENSO research through a range of coordination, synthesis, and outreach activities. These include a planned article reviewing the challenges in ENSO evolution, prediction and impacts over the past decade in the context of global warming; reviews of atmospheric teleconnections and biogeochemistry through the PATAC and BGC-PI working groups; and continued support for the development of and application of ENSO metrics. The PRP will also work to increase knowledge of ENSO research by making

ENSO webinars publicly accessible, by working with TPOS on a briefing note to increase awareness of the tropical Pacific observing system. More broadly, the Panel will continue to foster connections with international programmes and initiatives, including TPOS, GOOS, and PICES; endorse and support research networks such as NPOCE and SPICE; and collaborate with members of the TROPICS and TBI working groups hosted by the CLIVAR Climate Dynamics Panel.

Through these activities the CLIVAR PRP will continue to enable international coordination, knowledge exchange and capacity building to support continuous progress in Pacific climate and ENSO science.

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The CLIVAR Research Focus on Tropical Basin Interaction: Achievements and Legacy

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1. Inception

The tropical oceans interact through both oceanic and atmospheric pathways on various time scales including sub-seasonal to interdecadal time scales. The original motivation behind the Research Focus (RF) on Tropical Basin Interaction (TBI) was to quantify the strength of these interaction pathways and their importance for seasonal predictions through a set of coordinated global climate model (GCM) experiments. This GCM component was subsequently augmented with observational, paleo climate and conceptual modeling components and eventually led to a proposal for a CLIVAR RF. The RF commenced in early 2020 and concluded at the end of 2025. In this article, we explain the motivation and aims of the RF (section 1), give a brief summary of its activities and achievements (section 2), and discuss its legacy and future perspectives for TBI research (section 3).

1.1 Aims of the Research Focus

In the 1980s and 1990s, El Niño-Southern Oscillation (ENSO) and its global impacts on weather and seasonal climate variability received considerable attention. Over time, there was increasing interest in how the tropical Atlantic and Indian Oceans may in turn influence the tropical Pacific, leading to the concept of interbasin interaction. Variability in the northern tropical Atlantic (NTA) serves as a good example of such two-way interaction. In the boreal spring following an El Niño event, sea-surface temperatures (SSTs) in the NTA tend to warm due to ENSO induced teleconnections (Enfield and Mayer 1997). More recent studies have suggested that the NTA in return can influence ENSO evolution, with positive NTA anomalies leading to La Niña in the following winter (Ham et al. 2013). Understanding

these interaction mechanisms is therefore a necessary step for a comprehensive understanding of how the climate system works on interannual time scales, and it is crucial for improving seasonal predictions and managing climatic impacts associated with TBI. In addition, TBI may be an important element in how the climate system responds to external radiative forcing.

While interbasin interaction has attracted much attention, some studies have questioned its importance (Stuecker et al. 2017; Richter et al. 2021; Zhang et al. 2021; Jiang et al. 2023), especially with respect to Atlantic and Indian Ocean influences on ENSO. Meanwhile, many GCM experiments have aimed to quantify TBI but arrived at a wide range of estimates. Such discrepancies between studies can stem from differences in experiment design or differences in models and their systematic errors. Thus, one of the main goals of the RF TBI was to establish an experiment design that would be followed by all models. Different outcomes must then be due to model differences, allowing the influence of systematic model errors on TBI to be assessed.

In addition to the experimental aspect, the RF also endeavored to foster progress in other TBI-related research efforts, such as making paleo proxy data more accessible to climate researchers, clarifying the requirements for observation networks to address TBI, and to provide the community with conceptual models and statistical tools for the study of TBI. As a foundation for all the proposed research activities, the RF also aimed to review the current understanding of TBI.

As a CLIVAR RF, our main task was not to carry out research ourselves, but to foster research efforts.

This required community engagement and capacity building. Therefore, a central aspect of the RF was to organize conference sessions, bespoke workshops and summer schools.

1.2 Working Groups

To achieve our goals we established four Working Groups (WGs):

WG1: GCM Experiments

The goals of this WG were mostly to establish the experimental protocol and to engage with modeling centers in order to conduct the coordinated GCM experiments. In order for the wider community to benefit from these experiments, an important element was making the model output available to the public.

WG2: Conceptual and Intermediate Complexity Models and Statistical Approaches

While GCMs are important tools for climate research due to their relatively realistic representation of climate processes, they also have several drawbacks, including computational cost, difficulty of understanding their complex behavior, and common problems in representing small scale processes, such as cumulus convection. It is therefore desirable to have a hierarchy of models for aiding interpretation and physical understanding, and for offering a lightweight framework that facilitates experimentation. WG2 thus aimed to foster the development of conceptual models and statistical tools and to make these available to the public.

WG3: Observations

Many observational products exist but were not designed with the study of TBI in mind. The aims of WG3 were to take stock of currently available data and to make recommendations for the design of future observation networks.

WG4: Paleo data

Paleo proxies provide long term records that can potentially be useful for the study of TBI, provided that they carry information of relevant variables at sufficient temporal resolution. Many paleo proxies have been collected, but their use in TBI-related studies is hampered by a lack of awareness and expertise among TBI researchers. The goal of WG4 was therefore to provide guidance on the use of paleo records in TBI research.

2. Achievements

2.1 Research tools and resources

Coordinated GCM Experiments and TBI Model Intercomparison Project (TBIMIP)

A central objective of the RF TBI was to promote coordinated climate model experiments designed

specifically to investigate interaction among the tropical basins. This effort culminated in the development and implementation of TBIMIP, with participation from multiple modeling centers.

TBIMIP experiments were designed to isolate and quantify the influence of SST anomalies and atmospheric teleconnections from the tropical Pacific, Atlantic, and Indian Oceans. By applying a consistent experimental protocol across different coupled ocean-atmosphere GCMs, the project enabled researchers to compare model responses, identify robust mechanisms, and assess sources of uncertainty in simulated inter-basin interactions.

The coordinated experiments revealed both common features and important differences among models in representing tropical teleconnections (Wang et al., 2026, unpublished manuscript; Richter et al., 2026, unpublished manuscript). They also provided a valuable benchmark for evaluating the role of basin interactions in seasonal prediction, decadal variability, and climate change projections. Beyond the immediate scientific findings, TBIMIP established a collaborative infrastructure for model intercomparison and data sharing that will continue to support future studies of tropical climate dynamics.

Conceptual models and statistical tools

To complement the experiments with complex climate models, the RF also strove to provide conceptual modeling frameworks and statistical tools for the study of TBI. Such activities contributed to the development of the extended recharge oscillator (XRO; Zhao et al. 2024). This conceptual model enhances the well-known recharge oscillator for ENSO (Jin 1997) by including non-linearity and interaction with variability patterns in other basins. The resulting model displays high ENSO forecast skill, while at the same time permitting assessing the importance of TBI pathways. The code for this modeling framework has been made available on GitHub.

In a similar vein, an interbasin linear inverse model (LIM) has been developed (Kido et al. 2022) and will be made available to the community. Like the XRO, the interbasin LIM allows isolating the contributions of individual basins to variability and prediction skill. It is, however, a purely linear model and therefore even more lightweight than the XRO in terms of computation.

Discovering interaction pathways and quantifying their importance is one of the major goals of TBI. Causal effect networks (CENs) are a statistical tool to evaluate the causal relationships among time series and to quantify the strengths of the connections. Such tools have been used, for example, to examine the connections of the Indian summer monsoon to the tropics and midlatitudes (Di Capua et al. 2020).

The further use of CENs for the study of TBI has been promoted by members of the RF.

While GCMs are typically used to achieve as realistic climate simulations as possible, they can also be used in idealized settings. Dommenges and Hutchinson (2025) use a relatively low resolution coupled ocean-atmosphere GCM to explore interbasin interaction under various idealized basin configurations, such as a single basin, or three basins of equal size. This kind of experimentation can provide novel insights into how ocean basins interact and why present-day TBI behaves the way it does. The results from these simulations have been made available to the community.

Recommendations for an integrated pantropical observing system

A major outcome of the Observations Working Group was a community synthesis on the need for an integrated pantropical ocean observing system. The review (Foltz et al. 2025) brought together lessons from the tropical Pacific, Atlantic, and Indian Ocean observing system assessments and argued that tropical observing systems can no longer be designed only basin by basin. Interbasin interactions, such as the influence of the Indian Ocean Basin Mode and Indian Ocean Dipole on the Pacific and Atlantic, the Atlantic influence on ENSO and the Indian summer monsoon, and the oceanic links through the Indonesian Throughflow and Agulhas system, require observations that are coordinated across basins and across the air-sea interface. The synthesis therefore identified common gaps and priorities across the tropics, including sustained upper-ocean and surface-flux measurements, improved satellite continuity, better atmospheric boundary-layer observations, and stronger integration between physical, biogeochemical, and ecosystem variables.

Key recommendations include maintaining long-term observing backbones, expanding Argo, BGC Argo and Deep Argo, strengthening tide-gauge and coastal observing networks, improving real-time data delivery and FAIR data management, and using observing system experiments and observing system simulation experiments to quantify the value of different observing components for forecasts and reanalyses. These recommendations provide a practical observational legacy for RF TBI, linking process understanding, prediction, model evaluation, and societal applications.

Paleoclimate section in the NCAR Climate Data Guide

Paleoclimate proxy data are essential for improving our understanding of TBI on decadal and longer time scales, given the limited length of reliable instrumental observations. However, as highlighted at the WCRP-CLIVAR workshop on Climate Interactions among Tropical Basins in 2021 (Richter

and Keenlyside 2021), assessing the strengths and limitations of proxy data for TBI research is challenging for the climate dynamics community. To address this issue, RF TBI collaborated with the National Center for Atmospheric Research to develop a paleoclimate section in the Climate Data Guide (<https://climatedataguide.ucar.edu/>; Schneider et al. 2013). The section features articles by experts on four proxy types (corals, speleothems, tree rings, and lake sediments), as well as drought atlases derived from tree rings. In particular, the article on corals, which are instrumental in reconstructing tropical climate variability at sub-annual resolution, explains how geochemical records encode temperature and hydroclimate signals, including uncertainties, and provides links to publicly available data compilations (Lawman 2023). The Climate Data Guide is a widely used knowledge portal, and this section will help increase access to paleoclimate data not only within the TBI but also across the wider climate research community.

Proxy assimilation for reconstructing climate and improving model (PARCIM)

RF TBI members also contributed to the development of a new paleoclimate reanalysis framework (paleo-NorCPM, i.e. paleo-Norwegian Climate Prediction Model) that advances multi-century climate reconstruction by explicitly incorporating coupled ocean-atmosphere dynamics (Dalaiden et al. 2025). The system adapts the Norwegian Climate Prediction Model to assimilate more than 3,000 annually resolved proxy records (tree rings, corals, and ice cores) over the past ~500 years using an Ensemble Kalman Filter and a fully coupled Earth System Model prior. A key innovation is the combination of this offline data-assimilation reconstruction with a dynamically coupled ensemble, in which atmospheric circulation variability is constrained by the offline reconstruction. This approach allows an explicit representation of ocean dynamics and associated ocean-atmosphere interactions, which are absent in most existing paleoclimate reanalyses. The wind-nudged reanalysis exhibits more pronounced multi-decadal variability compared to the offline reanalysis. Overall, the framework provides a step toward fully coupled paleoclimate reanalyses and offers a new tool to investigate the role of TBI in low-frequency climate variability.

2.2 Community engagement and capacity building

Workshops

The first workshop organized by the RF TBI, the "WCRP-CLIVAR Workshop on Climate Interactions among the Tropical Basins", was held online-only in 2021 due to the COVID-19 pandemic (Richter and Keenlyside 2021). The workshop combined plenary talks, poster sessions, and breakout discussions across

the four TBI WGs, disseminating the latest research on interactions among the tropical Pacific, Atlantic, and Indian Oceans. Discussions during this workshop helped refine the goals of the four TBI WGs (section 1.2).

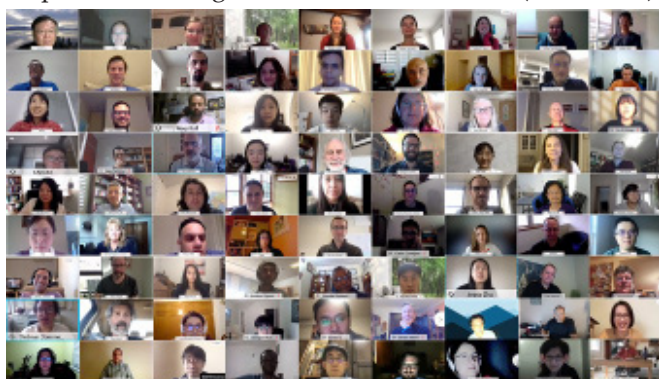


Figure 1. Participants of the 1st RFTBI Workshop "WCRP-CLIVAR Workshop on Climate Interactions among the Tropical Basins", held virtually in February 2021.

In 2023, the RF TBI had the opportunity to meet in person in Melbourne Australia for the first time after the pandemic. The "2023 CLIVAR workshop on the tropical Pacific and its interbasin interactions" was a joint initiative organized in collaboration with the Pacific Region Panel (PRP), Tropical Pacific Decadal Variability (TPDV) Working Group, ENSO conceptual model Working Group, and the RF TBI. The workshop connected over 130 participants from 26 countries in person and virtually, fostering collaboration within and across the three CLIVAR groups. The workshop provided an opportunity to review progress on the development of the coordinated modelling experiment protocol, with preliminary test simulations informing key design decisions, particularly regarding the SST restoring time scale and the latitudinal extent of the restoring region. The workshop also reviewed progress on complementary TBI activities, including organizing the joint CLIVAR Climate Dynamics Panel (CDP)-TBI summer school, writing a review article of the Tropical Pacific Decadal Variability, and identifying priorities for the ENSO Conceptual Model working group. Discussions reinforced the importance of TBI for understanding ENSO and decadal variability and highlighted the need for improved theoretical frameworks and coordinated modelling efforts.

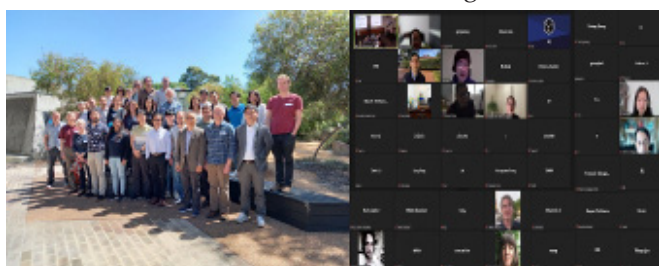


Figure 2. Attendees of the 2023 CLIVAR workshop on the tropical Pacific and its interbasin interactions, held at Monash University.

Later in 2023 the RF TBI had the opportunity to join efforts with the CDP and organize the "Workshop on

Atlantic Variability and Tropical Basin Interactions at Interannual to Multi-decadal Timescales: Mechanisms, Drivers and Impacts", held in Trieste Italy. The workshop brought together researchers working on TBI, Atlantic Multidecadal Variability (AMV), and Atlantic Meridional Overturning Circulation (AMOC) to address key scientific questions regarding the mechanisms governing TBI across timescales, the role of AMOC in shaping AMV, the representation of these processes in climate models, and their evolution under climate change. A major outcome of the workshop was the advancement of the coordinated multi-model TBI pacemaker experiments. Discussions helped refine the TBIMIP protocol, strengthened collaborations across modelling groups, and established priorities for the analysis of the forthcoming simulations.

Held in conjunction with the ICTP summer school on Atlantic Variability and Tropical Basin Interactions (described earlier in this article), the workshop also fostered interaction between senior and early-career researchers, helping to build capacity and consolidate an international research community working on TBI and climate predictability. Discussions during the workshop eventually led to a joint RF TBI-CDP review paper on TBI and AMV (Hu et al. 2025).

The workshop "Interaction among the tropical basins: observations and simulation" organized in 2024, held at Yonsei University in Seoul before the AOGS 2024 meeting, marked an important milestone in the implementation of the TBI Coordinated Experiments, bringing together modelling, observational, and palaeoclimate communities to evaluate the first results from the coordinated simulations and place them in the context of existing evidence on TBI. Presentations covered inter-basin teleconnections, seasonal-to-decadal predictability, climate model biases, emerging tropical climate modes, and the impacts of climate change on TBI. Discussions of the preliminary TBIMIP pacemaker and hindcast experiments helped refine strategies for analysing the coordinated simulations and identifying robust mechanisms across models. The workshop also strengthened collaborations across CLIVAR panels and the wider WCRP community, while the TBI Research Focus business meeting reviewed the status of the coordinated experiments and established plans for a community synthesis paper to consolidate emerging scientific understanding.

The last in-person meeting of the RF TBI was held in 2025 in Bali as part of the Pan-CLIVAR Meeting. Through interactive discussions and breakout sessions, the RF TBI convened a joint session with the PRP-PATAC and TROPICS Working Groups to identify common scientific challenges and opportunities for collaboration across the CLIVAR community. Several cross-cutting research priorities were identified, including the role of tropical Pacific model biases in limiting the simulation and prediction of TBI and global climate variability. The session also provided an opportunity to reflect

on the achievements and legacy of the RF TBI as it approached its conclusion. A key outcome was the agreement to continue its scientific activities through a new Working Group hosted by the CLIVAR CDP (now approved and currently in operation), ensuring continuity of the coordinated modelling experiments, community synthesis efforts, TBI webinar series, and future research on TBI.

Summer School in Trieste, 2023

A major achievement of the CLIVAR RF TBI was the organization of the Summer School on TBI held at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy in 2023. The summer school brought together early-career scientists and leading experts from around the world to examine the mechanisms, impacts, and predictability of interactions among the tropical Pacific, Atlantic, and Indian Oceans.

The program combined lectures, hands-on exercises, and collaborative discussions covering observational analyses, climate model simulations, statistical methods, and theoretical frameworks. Particular emphasis was placed on understanding the pathways through which variability in one tropical basin can influence climate conditions in other basins and on evaluating the implications of these interactions for seasonal-to-decadal prediction and climate change projections.

The school provided a valuable opportunity to build capacity within the international climate community and helped foster new collaborations among students and researchers working across different disciplines. Many of the participants have remained actively engaged in RF TBI activities, contributing to the development of new research initiatives and coordinated modeling efforts.

TBI webinar series

RF TBI hosted a dedicated webinar series during 2025 to share advances in TBI research (<https://www.clivar.org/tbi-webinar-series>). The series featured invited talks spanning observations, theory, modeling, and paleoclimate perspectives, with topics ranging from pan-tropical observing systems to conceptual models of ENSO and TBI, as well as insights from coral records and the role of TBI in climate change. By providing recorded sessions and covering diverse but interconnected themes, the series fostered interdisciplinary collaboration, helped synthesize current knowledge, and supported progress toward improved understanding and prediction of TBI and its global impacts.

2.3 Publications and Scientific Synthesis

The RF TBI stimulated a broad range of scientific studies and synthesis activities that significantly advanced understanding of TBI. One of the most important outcomes was TBIMIP, which established



Figure 3. Participants of the 2024 Interaction among the tropical basins: observations and simulation workshop.

a coordinated framework for investigating inter-basin teleconnections using climate models. The results provide new insights into the mechanisms linking variability across tropical ocean basins and offer a basis for systematically evaluating model performance.

In addition to the TBIMIP design paper (Richter et al. 2025), several review and synthesis papers were produced under the RF TBI framework, such as a comprehensive assessment of the relationship between Atlantic multidecadal variability and TBI (Hu et al. 2025). Efforts also included a review of the pantropical observing system and its role in monitoring and understanding inter-basin climate connections (Foltz et al. 2025), which reviewed common gaps across the tropical Pacific, Atlantic, and Indian Ocean observing systems and made recommendations for an integrated pantropical network. This paper broadened the RF TBI legacy beyond modelling and theory by providing an observational framework for sustaining and improving the measurements needed to understand tropical basin interactions in a changing climate.

Together, these RF TBI-related publications have helped establish a common scientific framework for the community and have provided an important reference for TBI researchers.

3. Legacy and way forward

Through workshops, summer schools, and coordinated research activities, the RF TBI fostered collaboration between modelling, observational, and palaeoclimate communities, while strengthening links with other CLIVAR panels and working groups, including the PRP, CDP, PATAC, and TROPICS.

Together with the CLIVAR community, the RF TBI successfully achieved its original objectives by developing the TBIMIP coordinated modelling protocol, now publicly available through the CMIP6Plus Experimental Protocols repository, providing the first community framework for systematically investigating TBI across climate models. In addition, the RF TBI delivered lasting community resources, including guidance on palaeoclimate proxy records relevant to

TBI, and advances in our understanding of TBI via conceptual, theoretical, and statistical approaches.

These collaborative efforts culminated in a comprehensive synthesis of the current understanding of TBI, identified key scientific gaps and priorities for future research, and established a legacy that continues through the new CLIVAR Working Group on Tropical Basin Interactions.

The TBI Working Group will build on the achievements of the RF TBI by providing a sustained framework for advancing understanding of interbasin interactions and their role in global climate variability and predictability. A central priority will be the continued development and coordination of the TBIMIP. As coordinated simulations from multiple modeling centers become available, the Working Group will facilitate community-wide analyses, develop common diagnostics and evaluation metrics, identify key model biases, and guide the design of complementary and follow-up experiments. It will also support the documentation, archiving, and dissemination of TBIMIP outputs through the Earth System Grid Federation (ESGF), ensuring broad accessibility and maximizing the scientific value of these coordinated efforts.

Beyond model intercomparison activities, the Working Group will promote research aimed at advancing the physical understanding and predictability of TBI. This includes fostering coordinated analyses that integrate climate model simulations, observations, reanalysis products, and theoretical frameworks. Particular emphasis will be placed on developing conceptual and reduced-complexity tools, such as the interbasin LIM, which provide an important bridge between theory and comprehensive Earth system models. TBIMIP can also be used to identify which pathways and regions are most important for TBI, thereby informing OSEs and OSSEs that can help assess which observations most improve reanalyses, forecasts, and process understanding. Through these efforts, the Working Group will seek to advance understanding of the mechanisms governing interbasin teleconnections, identify outstanding scientific challenges, and quantify their implications for climate variability and predictability across seasonal-to-decadal timescales.

The Working Group will also serve as a focal point for community engagement and international collaboration. Building on the success of the TBI webinar series, it will sustain regular scientific exchanges through webinars, workshops, and focused sessions at major conferences, while promoting participation across regions and career stages. Close coordination with related CLIVAR activities—including TROPICS, PATAAC, OMDP, and relevant regional panels—will foster interdisciplinary collaboration and strengthen connections across the broader climate research community.

Finally, the Working Group will lead synthesis activities, including the development of a comprehensive review paper and other community efforts that summarize recent advances, identify remaining knowledge gaps, and establish priorities for future research. We hope that these activities will provide useful guidance for TBI research, and that they will contribute to CLIVAR's goals of advancing understanding of ocean basin connectivity, tropical-extratropical teleconnections, and climate predictability.

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The Southern Ocean Region Panel: Advancing Antarctic Science through International Coordination and Collaboration

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1. Introduction

The Southern Ocean, which surrounds Antarctica, regulates global climate through its outsized contribution to oceanic heat and carbon uptake (Frölicher et al. 2015). The climatic importance of this region stems from its unique role in the global overturning circulation (Talley 2013), through which heat, freshwater, carbon, oxygen, and nutrients are redistributed across ocean basins and between the surface and abyssal ocean (Marshall and Speer 2012). Yet growing evidence indicates that the Southern Ocean is undergoing profound changes with potentially far-reaching impacts.

Rapid shifts in Antarctic sea ice (Purich and Doddridge 2023), accelerating ice shelf melt (Naughten et al. 2023), freshening of surface waters (Olivier et al. 2025), and changes in ocean circulation (Shi et al. 2021) are raising urgent scientific questions about their causes and consequences. Understanding and predicting these changes has important implications for sea level rise, Southern Ocean ecosystems, and climate variability far beyond the Antarctic region (Henley et al. 2020). At the same time, the remoteness and harsh conditions of the Southern Ocean make it one of the most challenging regions to observe and model.

In this context, the **CLIVAR/CliC/SCAR Southern Ocean Region Panel (SORP)** is a key coordinating body for the international research community. SORP brings together experts in observations and modelling to synthesize recent advancements in Antarctic science, identify major knowledge gaps, and outline research priorities. As a joint panel of the World Climate Research Programme (WCRP) Climate and Ocean: Variability, Predictability and Change project (CLIVAR), the Climate and Cryosphere project (CliC), and the Scientific Committee on Antarctic Research (SCAR), SORP sits at the intersection of ocean, climate, and cryosphere science. SORP's activities span scientific synthesis, community coordination, and capacity building through the organization of workshops, webinars, and summer schools. The panel also serves as a bridge to other major initiatives, including the

Southern Ocean Observing System (SOOS) and Antarctica InSync. In doing so, it helps ensure that observational and modelling priorities are aligned.

2. Building Community

A core function of SORP is fostering communication across the diverse Southern Ocean research community. Since 2023, SORP has hosted quarterly webinars, which have become an important venue for sharing new science and building connections across time zones and disciplines. The seminars typically attract 100-200 registrants, with 50-70 participants attending live. Recent talks spanned the breadth of Southern Ocean research, ranging from fine-scale modelling of ice shelf melt processes to satellite observations of air-sea interactions. This broad scope reflects SORP's priority to integrate perspectives from oceanography, ice dynamics, and climate modelling.

As such, the panel is intentionally diverse in terms of nationality, scientific expertise, and career stage. In 2025, SORP included 15 members representing 11 countries across 6 continents. The panel includes several early career researchers (ECRs), reflecting SORP's commitment to represent the next generation of Southern Ocean scientists. Supporting ECRs remains a priority, and three ECR panel members received CLIVAR support to attend the 2025 Pan-CLIVAR meeting in Bali, helping strengthen participation and cross-panel engagement.

3. Scientific Activities

SORP played a central role in the inception of the Southern Ocean Freshwater Input from Antarctica (SOFIA) initiative, which is endorsed as a CLIVAR task team. SOFIA is an international modelling effort to quantify the climate response to Antarctic meltwater, as well as the associated uncertainties. It does so through a coordinated multi-model ensemble of simulations based on a common experimental protocol (Swart et al. 2023).

Continued progress on SOFIA this year has included

the preparation and submission of analysis papers based on Tier 1 experiments (Pauling et al. 2026) and the running of higher tier experiments. Furthermore, several recently published SOFIA studies have highlighted the impacts of Antarctic meltwater on simulated sea surface temperature trends, atmospheric circulation, ice shelf basal melt and remote climate feedbacks (Kaufman et al. 2025; Xu et al. 2025; Muilijk et al. 2026; Zhang et al. 2026).

In addition, SORP is leading an observing system design effort focused on cross-shelf heat exchange. The task team, formed in late 2024, is using virtual Argo float release experiments to inform the sampling requirements needed to constrain ocean heat transport toward the Antarctic Ice Sheet. The Antarctic continental shelf is critically undersampled (Figure 1), and these results will help guide the planning of future field campaigns and optimal float deployment locations. The findings were presented at the 2026 Argo Steering Team Meeting, and manuscript submission is planned for late 2026.

4. Bridging the Two Poles

SORP also maintains close links with other CLIVAR panels, including the Northern Oceans Region Panel (NORP), the Ocean Model Development Panel (OMDP), and the Atlantic Region Panel (ARP). Together, these four panels organized a Polar Heat Workshop in Glasgow, Scotland in February 2026. The workshop focused on heat transport mechanisms and variability, as well as connections between the polar regions and lower latitudes.

A key aim of the workshop was to bring together expertise from the Antarctic, Arctic, and broader global climate communities. While the polar regions have often been treated as distinct systems, they share important similarities in their response to climate forcing. This same motivation underpinned the 2024 joint SORP-NORP summer school and workshop on polar climates, held at the International Centre for Theoretical Physics in Trieste, Italy. The event brought together 123 participants from a range of scientific backgrounds. A summary report detailing the outcomes of the 2024 workshop was submitted for publication at the end of 2025, and a review paper is in preparation following the 2026 workshop.

5. Looking Ahead

A major focus for SORP in the coming year is supporting the implementation of Antarctica InSync, a UN Ocean Decade Programme that aims to synchronize observational efforts across Antarctica and the Southern Ocean from 2027-2030. SORP has been actively engaged in Antarctica InSync through workshop organization, preparation of white papers, and national coordination efforts. Panel members are

helping shape scientific priorities, particularly around observing the coupled ice-ocean system.

These efforts come at a critical time for polar science, as the Southern Ocean continues to change rapidly (Silvano et al. 2025), with consequences that cascade across the Antarctic (Abram et al. 2025) and extend to the global scale. Meeting this challenge will require integrated observations and improved models, achieved through sustained international collaboration and strong community coordination. By connecting scientists across disciplines and nations, SORP provides a platform to facilitate this coordination and improve our ability to understand and predict the role of the Southern Ocean in a changing climate.

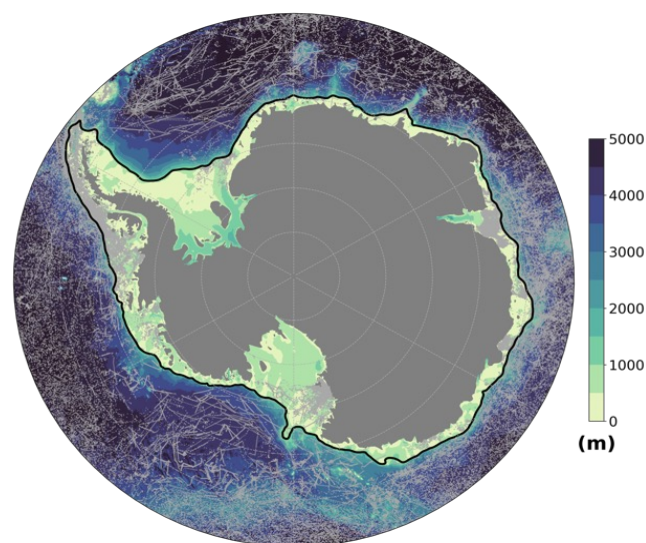


Figure 1. Map of Southern Ocean bathymetry (shading) with the 1000 m isobath highlighted by a bold black contour. Gray points indicate the locations of hydrographic observations from 2004-2021, including shipboard CTD casts, as well as data collected by Argo floats, instrumented marine mammals, and gliders (compiled by Spira et al. 2024).

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Winds of Change: two-decades of change in the four major Eastern Boundary Upwelling Systems (EBUS)

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Introduction

The eastern margins of the Atlantic and Pacific ocean basins are home to the world's four major eastern boundary upwelling systems (EBUS): the Canary-Iberia, the Benguela, the Humboldt and the California (Figure 1). Here, the predominantly equatorward winds drive the divergence of surface waters and continual replacement by deeper, colder and nutrient rich water. This process fuels primary production rates up to an order of magnitude higher than the global ocean average (Carr and Kearns 2003), shaping some of the largest ecosystems on the planet that support lucrative fishing industries and thus food security. Beyond their ecological importance, EBUSs exert a first order control on regional carbon balance and climate variability, as well as acting as natural laboratories for exploring the coupling between ocean, atmosphere and biogeochemistry (Capone and Hutchins 2013; Gruber et al. 2019).

Coastal upwelling is driven by alongshore winds generated by the pressure gradient between the oceanic subtropical high pressure systems and continental summer low pressures. While early hypotheses suggested that anthropogenic climate change would uniformly enhance these winds by intensifying the coastal lows (Bakun 1990), a revised hypothesis points to the poleward displacement of the oceanic high pressure systems strengthening upwelling favourable winds at poleward latitudes and reducing them at equatorward ones (García-Reyes et al. 2015; Rykaczewski et al. 2015; Wang et al. 2015).

The scientific exploration of the four major EBUSs has evolved from early regional observations and fishing records into structured, multidisciplinary field campaigns. Over the past century these efforts have transformed the simplified theoretical understanding of upwelling dynamics (Ekman 1905; Sverdrup 1938) into integrated system approaches that incorporate

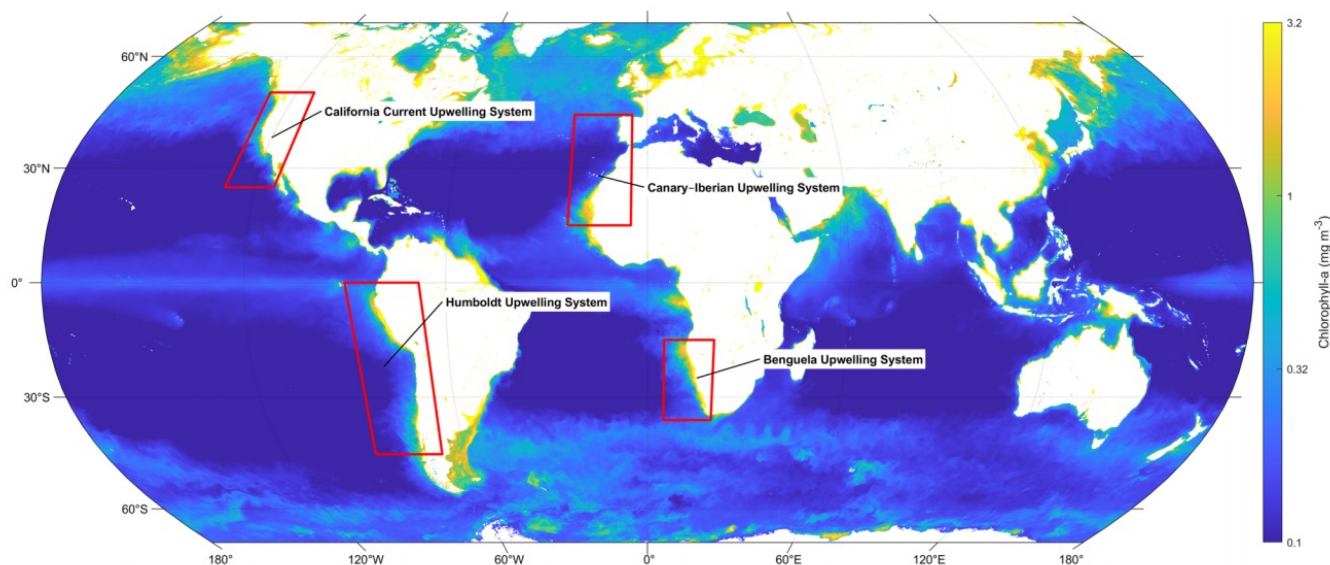


Figure 1: Global distribution of annual mean chl-a concentration (mg m^{-3}) derived from daily merged Level-4 satellite ocean-colour products averaged over the period August 2024-July 2025. It indicates the world's four major eastern boundary upwelling systems and that they are regions of high biological activity.

ocean, atmosphere, biogeochemistry and ecosystem feedbacks. The recently published review by Machín et al. (2026), traces this 100-year evolution and evaluates major environmental shifts, reflected in surface wind stress (ECMWFs ERA5 reanalysis product), sea surface temperature (SST: GHR SST Level 4 MUR), chlorophyll (MODIS-Aqua Level 3) and fishery data (Sea Around Us database) over the last two decades for each of the EBUSs. Here, we provide a summary of these recent decadal trends.

Benguela Current Upwelling System (BCUS)

Other than a reduction along the central BCUS coast, long term wind trends over the past 20 years in BUS indicate an intensification northward of 34°S reaching a maximum increase of $\sim 0.5 \text{ m.s}^{-1}.\text{year}^{-1}$ in the southern BCUS where the dominant wind direction remains upwelling favourable (Figure 2). On the other hand, the weaker intensification in the northern BCUS is coupled with an anticlockwise rotation, thereby resulting in a tendency toward less upwelling-favourable winds. Toward the south of the continent there is a significantly negative trend in wind intensity ($\sim 0.08 \text{ m.s}^{-1}.\text{year}^{-1}$) along with an anticlockwise rotation of the the wind direction, which implies an increasingly more upwelling favourable wind field where the coast is more zonally-oriented. These trend patterns are consistent with the southward displacement of the South Atlantic High Pressure System. The spatial distribution of SST trends partially mirrors these wind dynamics but underscores the importance of regional ocean advection processes (Figure 2). The southern

BCUS shows a coastal cooling trend, which peaks and is significant between 32°S and 24°S ($\sim -0.08^{\circ}\text{C}.\text{year}^{-1}$), which is consistent with the upwelling favourable wind intensification in this region. In contrast, driven by a reduction in upwelling-favorable winds, the northern Benguela experiences a warming trend that intensifies from $0.01^{\circ}\text{C}.\text{year}^{-1}$ at 24°S to $>0.06^{\circ}\text{C}.\text{year}^{-1}$ at its northernmost boundary. Given the relatively small change of upwelling favourable winds in the far north, increased poleward heat transport is a likely candidate for this extreme warming. Advection processes may also be the reason that the central Benguela demonstrates a slight cooling signal, despite the decrease in upwelling-favourable winds.

Canary-Iberia Upwelling System (CIUS)

Decadal trends in the nearshore wind intensity and direction across the CIUS are far from homogeneous (Figure 3). Most striking is the pronounced negative trend centered in the lee of the Canary Islands. In this area, wind speeds have decreased by $>0.03 \text{ m.s}^{-1}.\text{year}^{-1}$, accompanied by a clockwise rotation of the wind vectors. Though weaker ($\sim 0.02 \text{ m.s}^{-1}.\text{year}^{-1}$), this negative trend and clockwise rotation persists along the coast from 27°N to the northern edge of the Gulf of Cadiz ($\sim 37^{\circ}\text{N}$) where the clockwise rotation intensifies. Further south, off the Mauretanian and Senegalese coasts (17-23°N), trends are more modest, with increases of no more than $\sim 0.01 \text{ m.s}^{-1}.\text{year}^{-1}$. Off the Iberian Peninsula there is a significant increase in the wind intensity and a strong clockwise rotation in the direction. These patterns may reflect an intensification

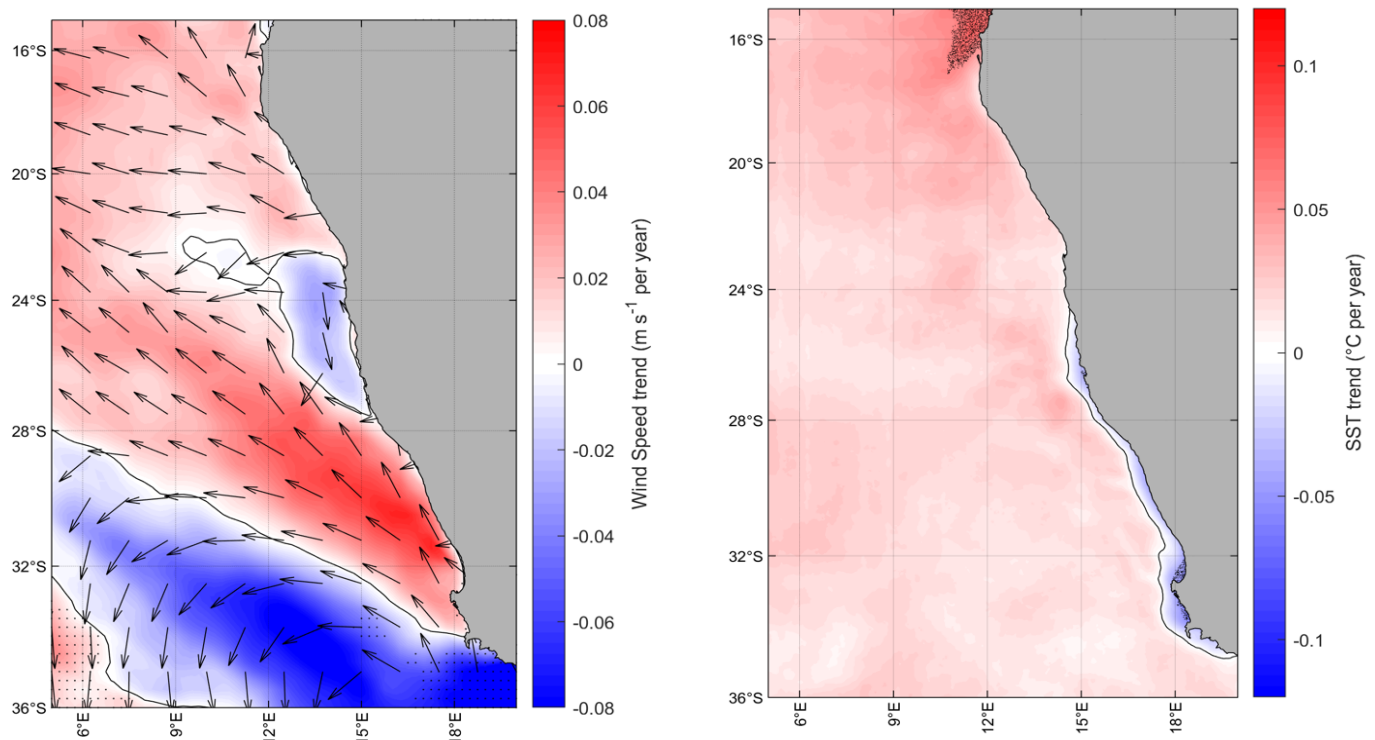


Figure 2: Linear trend of 10-m wind speeds and direction over the Benguela Current Upwelling System (left) and the SST trends (right), over the 2002-2024 period.

of the north eastern trades or shifts in the position of the Intertropical Convergence Zone (ITCZ) and possibly the poleward extension of the subtropical high pressure system. The spatial distribution of SST trends reveals a compelling contrast between the open ocean and the coastal upwelling zone (Figure 3). Offshore, SST trends are positive and typically range between 0.01 and $0.03^{\circ}\text{C}\cdot\text{year}^{-1}$, with slightly weaker trends ($<0.01^{\circ}\text{C}\cdot\text{year}^{-1}$) observed south of the Canary Islands, suggesting a latitudinal attenuation of the warming signal in the tropical transition zone. This

warming signal is consistent with the reduction in upwelling favourable winds in the lee of the Canary Islands and along the coast from central Morocco to the Gulf of Cadiz. In sharp contrast, is a narrow strip of cooling along the central Moroccan coast between about 24 – 32°N that is significant and most intense ($>0.04^{\circ}\text{C}\cdot\text{year}^{-1}$) in the southern part of this region, where the upward trend in upwelling favourable winds is significant.

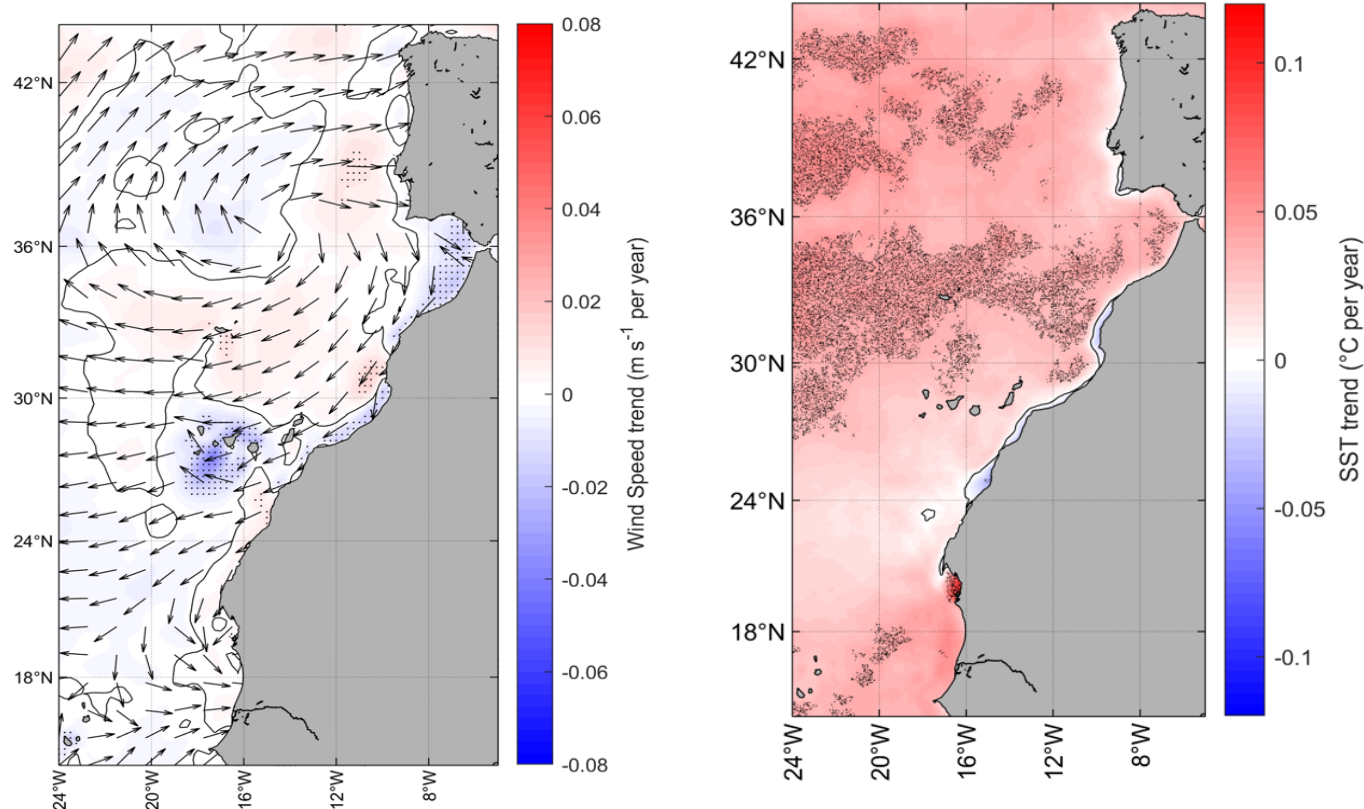


Figure 3: Linear trend of 10-m wind speeds and direction over the Canary-Iberia Upwelling System System (left) and the SST trends (right), over the 2002-2024 period.

Humboldt Current Upwelling System (HCUS)

Over the past couple of decades, the HCUS has experienced a relaxation of alongshore winds along the coasts of Peru and northern-central Chile (3 – 27°S : with a maximum of $>0.08\text{m}\cdot\text{s}^{-1}\cdot\text{year}^{-1}$), whereas a slight intensification of about $0.02\text{m}\cdot\text{s}^{-1}\cdot\text{year}^{-1}$ occurs toward south-central Chile (Figure 4). The results indicate that the negative trends off Peru are statistically significant over a band extending to ~ 400 km offshore, confirming a robust and widespread reduction in upwelling-favourable winds in this region. These results indicate that the climate-driven poleward shift in the position and intensity of the South Pacific Subtropical High are generating contrasting wind trends along the HCUS. The SST trends along the HUS show a spatial pattern that closely matches the distribution of surface wind trends. Figure 4 illustrates an extended warming along the northern HCUS, with trends reaching $+0.06^{\circ}\text{C}\cdot\text{year}^{-1}$, especially off Peru, which aligns with a relaxation of alongshore winds

and a reduction in upwelling strength. These positive trends are statistically significant in the northern part of the domain, north of $\sim 5^{\circ}\text{N}$, extending offshore towards the equator. Conversely, a cooling trend (-0.04 to $-0.08^{\circ}\text{C}\cdot\text{year}^{-1}$) appears along the south-central Chilean coast, where upwelling-favourable southerly winds have grown stronger in recent decades. This intensified coastal cooling supports the idea that increased wind stress is driving more vigorous coastal upwelling and entrainment of colder subsurface waters, resulting in a sustained decline in SST.

California Current Upwelling System (CCUS)

Upwelling-favourable winds have slightly increased in the central CCUS (32.5 – 42.5°N) by approximately $0.01\text{m}\cdot\text{s}^{-1}\cdot\text{year}^{-1}$ throughout the central area with a significant maximum of about $0.02\text{m}\cdot\text{s}^{-1}\cdot\text{year}^{-1}$, centered on 32°N (Figure 5). At the northern and southern edges of the system is a reduction in wind

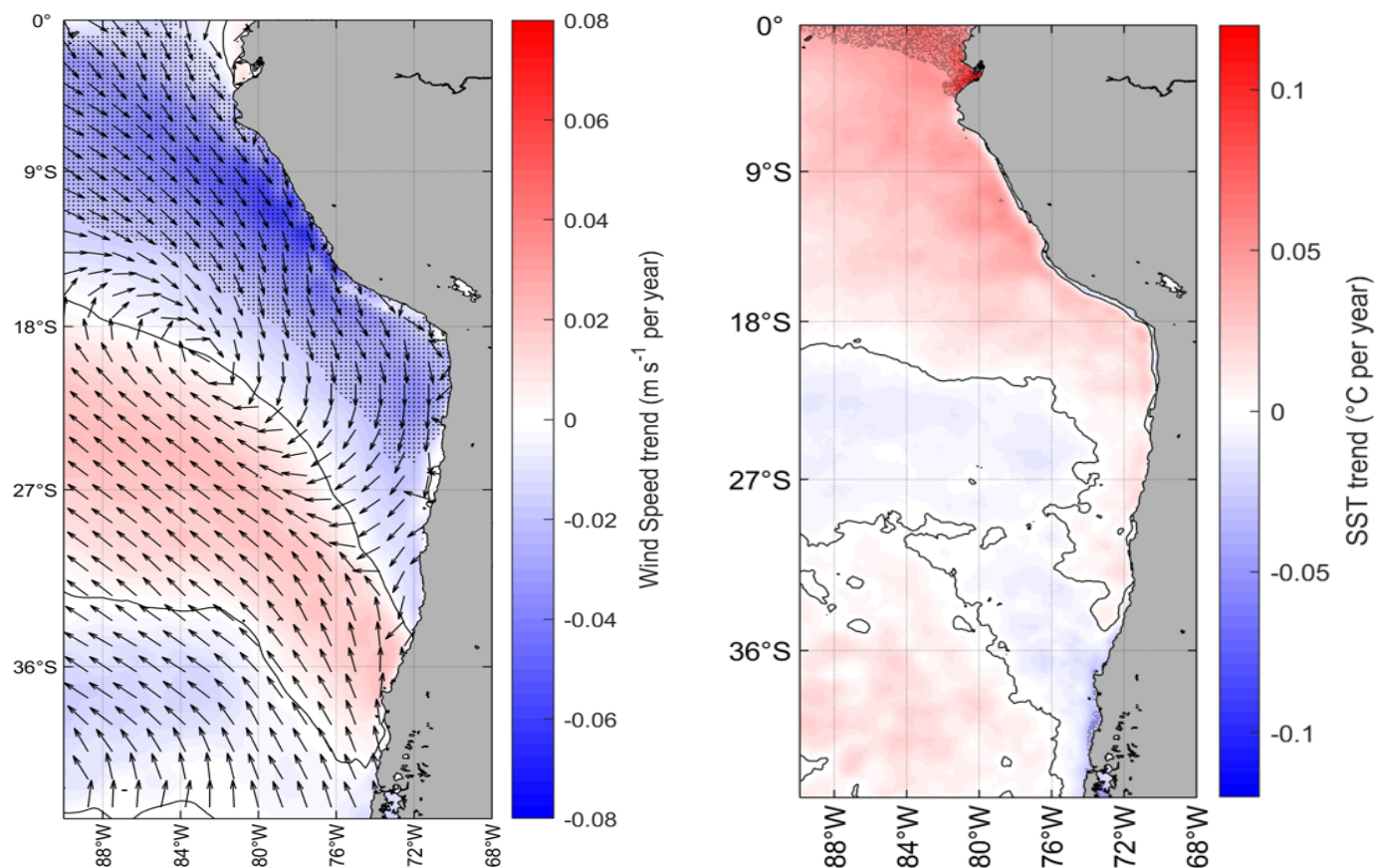


Figure 4: Linear trend of 10-m wind speeds and direction over the Humboldt Current Upwelling System System (left) and the SST trends (right), over the 2002-2024 period.

intensity of approximately $-0.01 \text{ m.s}^{-1}.\text{year}^{-1}$, with maximum and significant reduction in the far southern part of the region ($<0.02 \text{ m.s}^{-1}.\text{year}^{-1}$). The long term SST trends (Figure 5) in the CCUS are generally decoupled from the trend in the winds with dominant widespread warming that are significant along the central and southern coastal sectors (of approximately $0.4 \text{ }^{\circ}\text{C}.\text{year}^{-1}$). Despite the slight increase in upwelling favourable winds, the coastal warming along the central CCUS suggests that the potential increase in upwelling does not counteract the effect of other warming processes. On the other hand, the significant warming south of 27°N aligns directly with the observed relaxation of the upwelling favourable winds.

Biological response

The ultimate consequence of these climate trends lies in their downstream biogeochemical and ecological responses. Over the last two decades of global warming, satellite chlorophyll observations (Figures 27 to 30 in Machín et al. 2026) reveal a striking pattern of stability across all four of the major EBUSs. This suggests that primary productivity has not significantly changed, indicating that the core physical-biological upwelling dynamics supplying nutrients to the surface have remained fundamentally consistent. However, in stark contrast to the relatively stable lower trophic levels, significant changes to higher trophic levels is

observed. Key pelagic fish in the HCUS, CIUS and the CCUS have all suffered huge declines in the last 20 years. For instance, the catch of Peruvian anchoveta has halved since 2000, Chilean anchoveta and small pelagic catches collapsed to historic lows after 2014 and 2015. Along the Iberian coast of the CIUS, catches of European pilchard experienced a dramatic collapse from over 50000 tons per annum in the early 2000s to a mere 10000 tons. Similarly, the CUS witnessed a total collapse of its dominant South American pilchard fishery, from 100,000 tons to its collapse in 2018, driven by overfishing and intense environmental variability. The sole exception to these catastrophic declines occurs in the Benguela Current where fisheries remain balanced and stable. Although the larger South American pilchard catches collapsed to near zero by 2020, the catches of smaller sardinellas more than doubled during the same period, keeping the total biomass of small pelagics stable and reflecting a healthy, sustainability managed marine ecosystem.

Ultimately, while lower trophic levels show remarkable resistance to climate-driven changes, the higher trophic levels are strongly impacted across the majority of the world's EBUSs. The uniform collapse of these critical forage fish species across the Humboldt, Canary-Iberian and California systems, in spite of continued primary productivity, suggests that human extraction via overfishing is the primary cause.

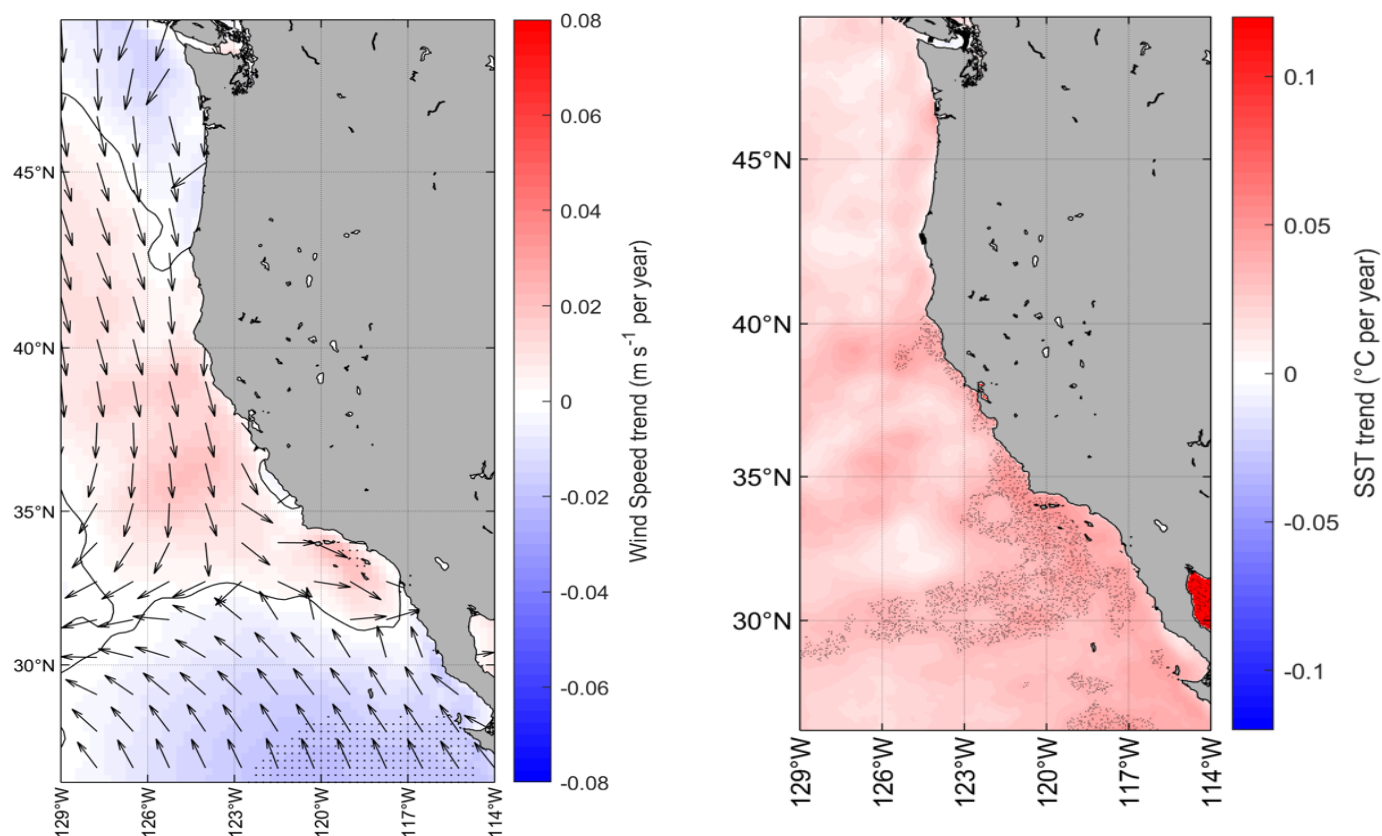


Figure 5: Linear trend of 10-m wind speeds and direction over the California Current Upwelling System System (left) and the SST trends (right), over the 2002-2024 period.

Conclusions

By analysing recent decadal trends across the Benguela, Canary-Iberian, Humboldt and California upwelling systems, this review highlights the common role of climate-driven physical changes. The most consequential for EBUSs being the poleward shifting high pressure systems leading to specific spatial patterns of SST and wind stress trends. While this summary only focuses on the long term annual trends, these patterns are modulated by the strong seasonal signal that dominates in each of the EBUSs and that are described in the full manuscript (Machín et al. 2026). In the BCUS, CIUS and the HCUS the poleward shifting high pressure systems manifest as increasing winds toward the poleward regions, and decreasing toward the equatorward regions. In the CCUS, these changes are less clear than in the other EBUSs (Bograd et al. 2023) as interannual and decadal variability are large in this system (Bonino et al. 2019). Despite these distinct physical perturbations across all four systems over the past two decades, surface chlorophyll concentrations have remained remarkably stable, even as human overfishing has simultaneously precipitated severe, widespread collapses in higher-trophic-level forage fish stocks.

While the general long term trends observed in the BCUS, CIUS and HCUS are consistent with the poleward shifting pressure systems, synoptic-scale

upwelling events are projected to change as migratory anticyclone tracks also shift poleward under continued warming, thereby altering the frequency of stronger upwelling wind conditions (Aguirre et al. 2019). However, future changes in coastal vertical velocities may become partially decoupled from surface wind forcing due to the increasing stratification of the upper ocean, which could modify the efficiency of wind driven upwelling (Oyarzún and Brierly 2019). These results underscore the necessity of high-resolution climate models to support improved understanding of the future of EBUSs.

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MER-EP initiative: the Marine Environment Reanalyses Evaluation Project

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Motivation

Ocean reanalyses that combine ocean models with observations through data assimilation schemes are alternative data resources to study ocean and climate changes and understand ocean and climate dynamics compared to pure observations or numerical models based datasets. The advantage of ocean reanalyses data is that they provide temporal and spatial consistent ocean state back in time compared to observation datasets and they correct model biases of the ocean state using observations as reference data compared to pure numerical model simulations. These advantages of ocean reanalyses allow a wide range of usage of the datasets, for example, ocean processed based scientific studies, monitoring and understanding ocean variability and changes, reference data for evaluating climate models, boundary conditions for regional models, initial conditions for ocean forecasts and predictions etc. In particular, the fast growing field in the artificial intelligence for ocean forecast requires high quality of ocean reanalyses to train the forecast in order to provide trustable AI-based ocean forecasts. Therefore, the performance of ocean reanalyses, or in another word, the quality of ocean reanalyses is the backbone of the usage of ocean reanalyses in different applications or studies.

The increasing use of ocean reanalyses has motivated international efforts to assess their quality, consistency, and associated uncertainties. Early coordinated activities conducted under the CLIVAR (Climate and Ocean: Variability, Predictability and Change) and GODAE (Global Ocean Data Assimilation Experiment) programmes established the foundations for systematic comparisons between ocean syntheses and reanalyses and highlighted the value of multi-system approaches for quantifying uncertainty (Stammer et al 2010). These efforts were later expanded through the Ocean Reanalysis Intercomparison Project (ORA-IP), which brought together products from operational and research centres worldwide. ORA-IP demonstrated that ensemble approaches based on multiple reanalyses provide a robust framework for evaluating confidence in large-scale ocean indicators while also revealing persistent discrepancies associated with data-sparse regions, deep-ocean variability, salinity estimates, and polar processes (Balmaseda et al. 2015). Since

ORA-IP, ocean reanalysis systems have undergone substantial evolution. Higher model resolutions, improved atmospheric forcings, enhanced observed data and advances in data assimilation techniques have significantly modified the landscape of ocean reanalysis production. In parallel, the range of applications has expanded beyond physical oceanography to include marine biogeochemistry, ecosystem monitoring, sea ice variability, and ocean surface waves. These developments have created the need for a new coordinated assessment effort capable of evaluating the current generation of reanalyses and addressing emerging user requirements.

To address these challenges, the Copernicus Marine Service organized the Ocean Reanalyses Workshop in Toulouse (France) in October 2023 (Yang et al. 2025). The workshop gathered reanalysis producers, scientific experts, operational centres, and users from a wide range of disciplines to review recent progress, identify remaining challenges, and discuss future priorities for the community. A central outcome of these discussions was the recognition that future intercomparison activities should place greater emphasis on user-oriented evaluation frameworks and application-driven performance metrics. The workshop recommendations highlighted the importance of strengthening interactions between producers and users and of extending evaluation activities across ocean physics, biogeochemistry, sea ice, and wave applications. These conclusions ultimately led to the establishment of the MER-EP project (<https://oceanpredict.org/un-decade-of-ocean-science/mer-ep-un-decade-project/>) as a coordinated international initiative within the framework of the United Nations Decade of Ocean Science for Sustainable Development (<https://oceandecade.org/actions/marine-environment-reanalyses-evaluation-project/>). The project is endorsed by the Ocean Decade programmes OceanPredict/ForSea and is supported by international initiatives including CLIVAR GSOP (Global Synthesis and Observations Panel).

Project presentation

The MER-EP initiative builds upon more than a decade of international efforts dedicated to the evaluation and intercomparison of ocean reanalyses. The project

was officially launched at the Third United Nations Ocean Conference (UNOC3) in June 2025 and will be conducted over the 2025–2029 period. MER-EP relies on contributions from operational forecasting centres, research institutions, universities, and environmental agencies from different countries. While ORA-IP established a robust framework for assessing uncertainties in physical global ocean state estimates and demonstrated the value of multi-reanalysis approaches, the scientific and operational landscape has evolved considerably over the last decade. These changes have created the need for a renewed international assessment effort capable of addressing contemporary scientific challenges while responding directly to user needs. MER-EP was conceived to meet this objective by providing a coordinated framework for evaluating both global and regional ocean reanalyses across a wide range of disciplines and applications. In this respect, MER-EP can be viewed as the next step in the evolution of community-based ocean reanalysis assessment, extending the legacy of ORA-IP toward a more integrated, interdisciplinary, and user-oriented perspective.

The central premise of MER-EP is that the value of an ocean reanalysis cannot be only assessed solely through traditional validation metrics. While comparisons against observations remain essential, the practical usefulness of a reanalysis ultimately depends on its ability to support specific scientific, operational, and societal applications. Consequently, MER-EP adopts a dual evaluation strategy. On one hand, the project investigates the consistency, robustness, and uncertainty of ocean reanalyses using established scientific diagnostics and with published results. On the other hand, it evaluates, in a second time, their fitness-for-purpose through a series of application-oriented use cases co-developed with end users. This approach aims to bridge the long-standing gap between product development and product usage, ensuring that future advances in ocean reanalysis systems are guided not only by scientific performance metrics but also by real-world requirements. A major advancement of MER-EP relative to previous reanalysis assessment efforts is also its broadened scope. Rather than focusing exclusively on physical oceanography, the project considers the full spectrum of marine system components, from ocean circulation to sea ice, surface waves, and biogeochemical processes. This expanded framework is structured around three interconnected themes: Blue Ocean, dedicated to physical ocean applications; White Ocean, focused on polar and sea-ice processes; and Green Ocean, addressing marine biogeochemistry and ecosystem dynamics. To translate these broad scientific themes into concrete evaluation activities, MER-EP relies on a collection of user-oriented “use cases” (Figure 1). The organizational structure has been designed to remain flexible and inclusive, allowing new participants to

join existing activities or propose additional areas of investigation as the project develops. These use cases have been identified through discussions with users from both scientific and operational communities and are intended to address questions for which ocean reanalyses provide essential information. Although addressing different scientific questions, all use cases follow a common evaluation framework based on the definition of scientific and user requirements, the selection of relevant reanalysis products, the establishment of performance metrics, and the assessment of uncertainties and fitness-for-purpose. For all these use cases, the primary objective of MER-EP is to improve our understanding of the ocean through a better assessment of the reliability, consistency, and usability of ocean reanalyses.

To summarise, the project aims to:

- evaluate global and regional ocean reanalyses across a broad range of variables and temporal scales;
- identify strengths and limitations of existing products;
- quantify uncertainties through coordinated multi-system analyses;
- promote common evaluation methodologies;
- foster interactions between reanalysis producers and users;
- provide recommendations for future developments in ocean reanalysis systems.

The project is overseen by a Scientific Steering Committee composed of internationally recognized experts spanning the various scientific domains covered by MER-EP (<https://oceanpredict.org/un-decade-of-ocean-science/mer-ep-un-decade-project/steering-committee/>). The committee provides strategic and scientific guidance, follows the progress of the use cases, promotes interactions with related international activities, and contributes to the synthesis of project outcomes and recommendations. Care has been taken to ensure a balanced representation of expertise, geographical regions, and scientific communities.

MER-EP is conceived as an open international initiative. Participation is not restricted to current project members, and contributions from new institutions, scientific groups, and stakeholders are actively encouraged. The project welcomes proposals for new use cases, contributions to existing activities, and leadership of specific tasks.

Also, a dedicated special issue (https://os.copernicus.org/articles/special_issue1396.html) is also planned to provide a forum for publications arising from the project, including methodological developments, intercomparison studies, and application-oriented analyses.

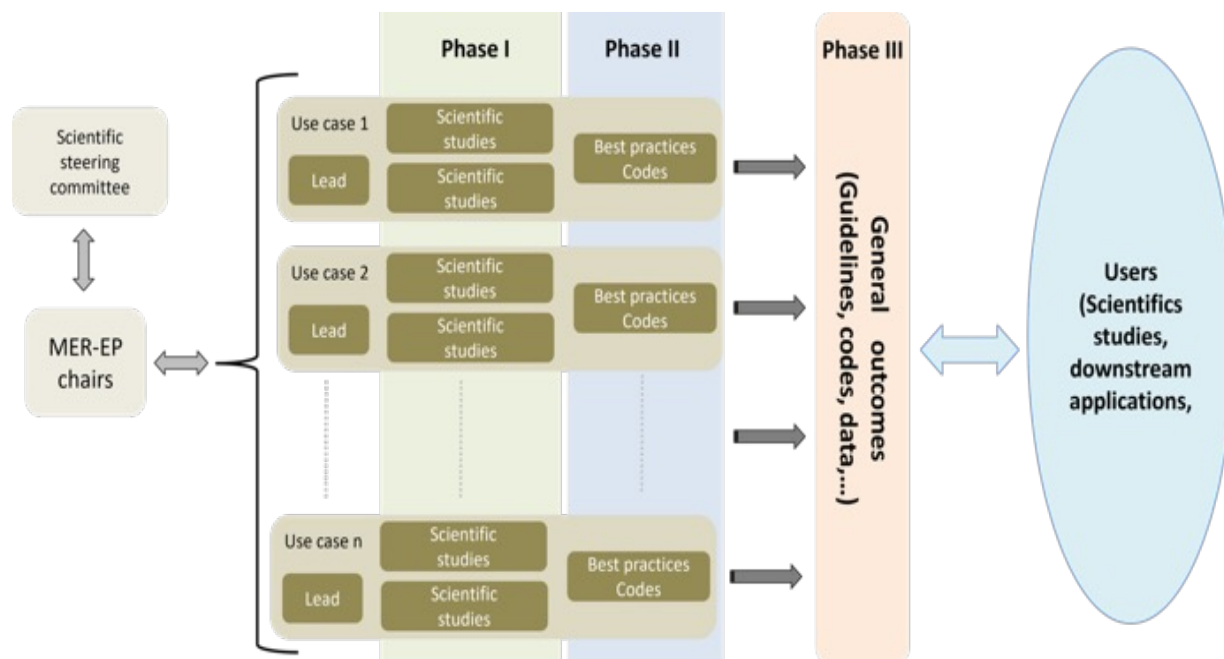


Figure 1. MER-EP general design and steps.

Conclusions and perspectives

MER-EP has been developed to address this need by bringing together producers and users of ocean reanalyses within a coordinated international initiative. Building on the legacy of earlier intercomparison projects, MER-EP expands the scope of evaluation beyond physical oceanography to include sea ice, ocean waves, and marine biogeochemistry, while placing user-oriented applications at the centre of the assessment strategy. Through its multidisciplinary structure and use-case-based approach, the project aims to improve both the scientific understanding and the practical usability of global and regional ocean reanalyses. By fostering collaboration across institutions, disciplines, and application domains, MER-EP will contribute to strengthening confidence in ocean reanalysis products and to enhancing their value for research, operational services, and decision-making activities throughout the UN Decade of Ocean Science for Sustainable Development.

The first priority for MER-EP over the coming years will be to maintain the momentum generated by the project launch and to further expand participation across the international ocean community. Particular attention will be devoted to consolidating the organizational structure, strengthening interactions among participants, and supporting the development of existing and emerging use cases.

As several use cases are already progressing rapidly, the publication of early scientific results will represent an important milestone for the project. These initial studies will help demonstrate the capabilities and limitations of current ocean reanalyses for specific

applications and provide tangible examples of the added value of the MER-EP framework.

Beyond the intercomparison activities themselves, MER-EP aims to promote ocean reanalyses as mature and validated reference datasets for a broad range of applications. These include process studies, model evaluation and benchmarking, initialization of prediction and projection systems, and emerging data-driven approaches such as machine learning and artificial intelligence. By improving confidence in reanalysis products and documenting their strengths and limitations, the project will contribute to expanding their use across both scientific and operational communities.

Another important objective is to facilitate access to ocean reanalysis products and associated methodologies. To this end, MER-EP will promote the development and dissemination of shared datasets, common evaluation tools, and open-source processing scripts that can be readily used by researchers, operational centres, and downstream users. Such resources will help improve reproducibility, encourage community engagement, and lower barriers to the use of ocean reanalyses.

Finally, one of the long-term ambitions of MER-EP is to establish community guidelines and best practices for the evaluation and use of ocean reanalyses. Drawing upon the results of the different use cases, the project will progressively synthesize recommendations regarding product selection, uncertainty assessment, and fitness-for-purpose considerations. These guidelines are expected to provide valuable support for both experienced users and newcomers seeking to exploit ocean reanalysis

products in scientific, operational, and societal applications.

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Uncertainties in Precipitation Datasets across Different Timescales: The Case of South America

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1. Introduction

During the 2026 Coupled Model Intercomparison Project (CMIP) Community Workshop, the World Climate Research Programme (WCRP) - Global Precipitation Experiment (GPEX) organized a symposium that highlighted a fundamental challenge for climate science: the quality and availability of precipitation datasets used for climate studies and model evaluation, particularly in the context of high-resolution simulations. One of the key questions raised in the GPEX Science Plan is: *“What are the sources and magnitude of uncertainties in quantitative precipitation estimates over global land and ocean, particularly in regions of vulnerable populations and limited observing capabilities, and how can we address them?”* (Zeng et al. 2025).

GPEX recognizes that advances in precipitation prediction depend not only on improvements in numerical modeling, but also on enhanced observational networks, rigorous evaluation of precipitation products, and greater and reliable integration of surface, radar, and satellite observations. The efforts of GPEX and other WCRP activities are largely community-driven and rely on voluntary international collaboration. While these initiatives are making significant progress in coordinating global efforts, addressing long-standing observational deficiencies remains a major challenge, particularly in regions with sparse monitoring networks. South America is one such region, where the density of rain gauges, weather radars, and long-term observational records remains insufficient in many areas, limiting our ability to accurately characterize precipitation variability, extremes, and trends. The need for expanded ground-based observations, targeted field campaigns, and sustained investment in monitoring infrastructure has been repeatedly recognized as essential for reducing uncertainties in precipitation estimates.

In parallel, studies have sought to quantify these uncertainties by intercomparing precipitation datasets across different temporal and spatial scales. From a

spatial perspective, these studies range from global/continental assessments (e.g., Beck et al. 2017; Sun et al. 2018; Gebrechorkos et al. 2024) to regional evaluations focused on South America. For example, Reis et al. (2022) compared the Tropical Rainfall Measuring Mission (TRMM)-based MERGE precipitation product (TRMM-MERGE) and the Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Global Daily Precipitation, provided by the National Oceanic and Atmospheric Administration (NOAA) (hereafter CPC), over Brazil and surroundings, for the period 1998–2017. They highlighted that both datasets present substantial differences across the studied region. De Menezes et al. (2026) compared the station-interpolated Brazilian Daily Weather Gridded Data (BR-DWGD) dataset, the CPTEC/INPE Combined Precipitation Product (MERGE), and the Fifth Generation European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis for Land (ERA5-Land) against station observations from Brazilian National Institute (INMET). BR-DWGD showed the highest agreement with observations, followed by MERGE and ERA5-Land.

In the Amazon Basin, Polaski et al. (2025) compared ERA5, Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS), the Global Precipitation Climatology Centre (GPCC) dataset, and Integrated Multi-satellite Retrievals for the Global Precipitation Measurement mission (IMERG) over the period 1980–2022. One of their main findings was that precipitation trends varied considerably among the datasets. Similarly, Sapucci et al. (2022) assessed CHIRPS and six additional products over the Amazon Basin and showed that all datasets performed poorly in the northwestern portion of the basin, with CHIRPS underestimating seasonal precipitation. In the Central Andes of Argentina, Rivera et al. (2018) found that CHIRPS overestimated seasonal precipitation totals during the cold semester (April–September).

Over southwestern South America, Benítez et al. (2024) evaluated satellite-based precipitation estimates at annual, monthly, and daily timescales using IMERG, Precipitation Estimation from Remotely Sensed

Information using Artificial Neural Networks (PERSIANN), PERSIANN–Cloud Classification System–Climate Data Record (CCS-CDR), and PERSIANN Dynamic Infrared–Rain Rate (PDIR-NOW) against observations for the period 2001–2020. Although all products reproduced the spatial pattern of annual precipitation, IMERG and CCS-CDR performed better at monthly timescales, while IMERG showed the best performance at daily scales. For the same region, Bettolli et al. (2026) assessed precipitation extremes using an ensemble of convection-permitting simulations, machine learning-based downscaling, and multiple observational datasets. They demonstrated that uncertainties among observational datasets were comparable to, and in some cases larger than, the spread among the simulations themselves.

Based on the previous discussion, this manuscript seeks to draw the attention of the broader climate community to the challenges faced by researchers working in South America when selecting datasets for climate analyses and model validation. These challenges are particularly critical for convection-permitting simulations, whose kilometer-scale resolution requires observations with high spatial density and fine temporal resolution. However, in many parts of the continent, sparse station networks and limited data availability compel researchers to rely on gridded products derived from interpolation, satellite retrievals, reanalyses, or combinations of these sources, each characterized by distinct uncertainties and biases. As a result, conclusions regarding model

performance may depend strongly on the choice of reference dataset (Beck et al. 2017). In this context, the primary objective of this study is to elucidate the uncertainties associated with South America precipitation datasets across multiple temporal scales.

2. Why Do Precipitation Datasets Differ?

Differences among precipitation products arise because they are derived from different combinations of rain-gauge observations, satellite estimates, and numerical weather prediction models. These inputs are processed using distinct retrieval, merging, interpolation, data assimilation, bias-correction, and quality-control methodologies (Carvalho 2020). The main type of precipitation products are described as follows.

Gauge-based products such as CPC (Chen et al. 2008) rely primarily on station observations. Their quality depends heavily on station density and the availability of long-term records. Satellite-derived products such as IMERG (Huffman et al. 2019), Global Satellite Mapping of Precipitation (GSMaP, Kubota et al. 2020), and PERSIANN (Sorooshian et al. 2014) estimate precipitation indirectly from cloud and microwave observations. While these datasets provide excellent spatial coverage, they are subject to retrieval uncertainties associated with cloud microphysics, topography, and precipitation type. Reanalyses such as ERA5 (Hersbach et al. 2020) assimilate multiple sources of data into numerical weather prediction systems. Although physically consistent, precipitation

Table 1 Main characteristics of the precipitation datasets considered in this study. Although all datasets were analyzed at the monthly scale, sub-daily analyses were additionally conducted using the 3-hourly MSWX and hourly ERA5 precipitation products.

Dataset	Data Type	Temporal Coverage	Temporal Resolution	Spatial Resolution	Spatial Coverage	Reference
MSWX	Multi-source meteorological product (satellites, reanalyses, and observations)	1979–present	3-hourly, daily, monthly	0.1° (~11 km)	Global	Beck et al. (2022) https://www.gloh2o.org/mswx/
CHIRPS v3	Satellite-based precipitation product calibrated with rain gauges	1981–present	Daily, pentadal, and monthly	0.05° (~5 km)	60° S–60°N	Funk et al. (2015, 2026) https://data.chc.ucsb.edu/products/CHIRPS/v3.0/
ERA5	Atmospheric reanalysis	1940–present	Hourly, daily, monthly	0.25° (~31 km)	Global	Hersbach et al. (2020) https://cds.climate.copernicus.eu/
CPC Unified	Gauge-based precipitation analysis	1979–present	Daily, monthly	0.5° (~55 km)	Global land areas	Chen et al. (2008) https://psl.noaa.gov/data/gridded/data.cpc_globalprecip.html
CMAP	Merged precipitation product (satellites, rain gauges, and numerical models)	1979–present	Pentadal, monthly	2.5° (~275 km)	Global	Xie and Arkin (1997) https://psl.noaa.gov/data/gridded/data.cmap.html

is not a direct observation and may contain systematic biases associated with model physics and data assimilation procedures. Hybrid products such as CMAP (Xie and Arkin 1997), CHIRPS (Funk et al. 2015, 2026) and MSWX (Beck et al. 2022) combine data from different sources. CMAP standard product blends gauge observations and satellite observations, while the enhanced product incorporates NCEP–NCAR reanalysis; CHIRPS combines satellite information with station observations, and MSWX has its historical part based on ERA5 data bias corrected and downscaled using high-resolution reference climatologies.

These products often provide realistic climatological patterns but may be affected by changes in station availability through time (Carvalho 2020). Consequently, no dataset can be considered a perfect representation of precipitation, particularly in regions where observational constraints are severe.

3. Dataset Selection Depends on the Scientific Application

This section examines precipitation datasets at multiple temporal scales (annual, seasonal/monthly, daily, and hourly). To illustrate these analyses, we focus on datasets spanning 1991 to the present (**Table 1**) allowing the calculation of the 1991–2020 climatological normal (WMO 2017).

Annual Mean and Trend Analyses: The use of precipitation time series from rain gauges and gridded datasets for calculating annual means and detecting long-term trends deserves particular attention. A common assumption is that a long observational record provides a reliable estimate of both climatological means and long-term changes. However, this assumption is often violated because the observational systems used to construct precipitation datasets evolve over time (Carvalho 2020).

To address this issue, **Figure 1a** illustrates the temporal evolution of the number of rain gauges incorporated into CHIRPS since December 1980. Counterintuitively, the total station count exhibits a progressive decline over time, a trend that runs contrary to the expectations of the scientific community. The variability in station counts arises from multiple factors that often differ across countries. Instruments may fail and remain unrepaired, and some stations are discontinued due to political or budgetary constraints. In other cases, recent observations exist but have not yet been released because of reporting delays (Carvalho 2020). Consequently, the station network used to construct gridded precipitation products is not temporally homogeneous.

The spatial distribution of the rain gauges available in

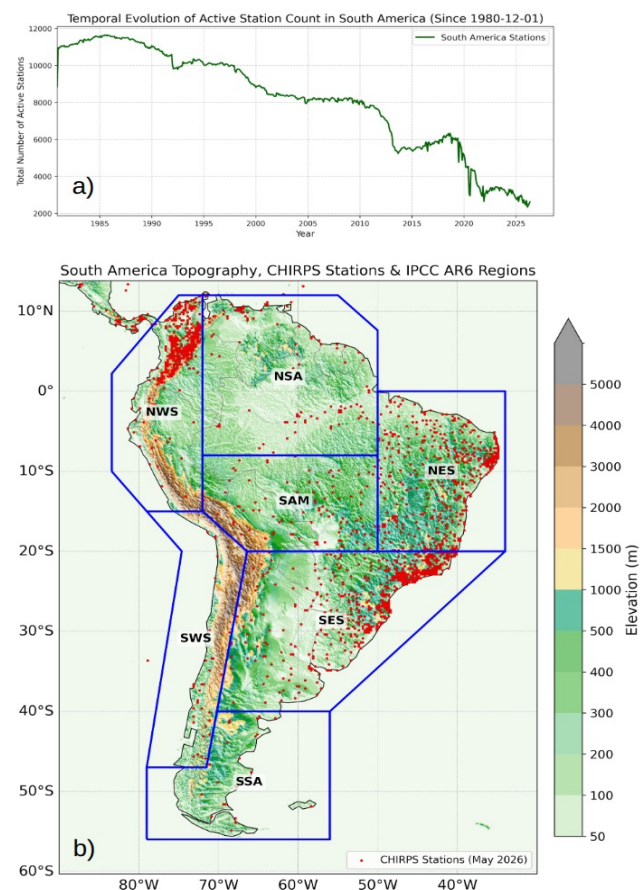


Figure 1 (a) Number of rain gauge stations utilized to create monthly CHIRPS gridded dataset from Dec 1980 to May 2026, and (b) number of stations available in May 2026, GTOPO30 South America topography (meters; Earth Resources Observation and Science (EROS) Center 2023), and IPCC-AR6 regions: NWS (North-Western South America), NSA (Northern South America), NES (North-Eastern South America), SAM (South American Monsoon), SWS (South-Western South America), SES (South-Eastern South America), and SSA (Southern South America).

South America in May 2026 is presented in **Figure 1b**. The highest station density occurs along the southern, southeastern, and northeastern coasts of Brazil, as well as in northwestern Colombia, which are regions with large concentrations of population (Carvalho 2020). In contrast, a vast area extending from the Amazon into Central-Western Brazil, which represents the core of the South American Monsoon System (SAMS; Reboita et al. 2025), has sparse station coverage (Carvalho and Nunes 2025). The limited coverage is partly attributed to the dense canopy of the Amazon rainforest; consequently, the majority of active stations in the Amazon basin are located along the course of the Amazon River (**Figure 1b**). The sparsity of stations in critical regions for the study of the SAMS limits the ability to investigate long-term variability and change in precipitation, including extremes events, with datasets that rely on observations from stations.

Despite these limitations, gridded precipitation datasets often provide realistic representations

of spatial climatological patterns. However, both precipitation magnitudes and long-term trends may be substantially affected by temporal changes in observational coverage (**Figure 2a**). This issue is particularly relevant in regions with sparse ground observations and in trend analyses that include the most recent years, even in areas with a relatively dense network of stations.

Figure 2a presents the annual mean precipitation across the entire South American continent derived from the datasets listed in **Table 1**, while **Figure 2b** shows the corresponding annual precipitation anomalies. Discrepancies exist among the datasets, with CPC providing the driest estimates, followed by CMAP, and ERA5 the wettest. Despite these differences in magnitude, all datasets generally reproduce the observed interannual variability of precipitation, with the timing of wet and dry years largely consistent across products. Furthermore, all datasets indicate a negative long-term trend over the entire continent. Only CMAP exhibits a non-statistically significant negative trend, which is likely because it is drier than the others before 2000, flattening the overall trend (**Figure 2a,b**). The agreement in interannual variability suggests that large-scale year-to-year fluctuations are relatively robust across products, whereas estimates of precipitation magnitude and long-term change remain considerably more uncertain.

A marked drying trend is particularly evident in the CPC dataset after 2004, which may partly reflect changes in station density rather than purely climatic signals. Polasky et al. (2025) also indicate discrepancies in precipitation trends over the Amazon are observed across datasets independently of the period of analysis. Other studies, such as the comparative analyses performed by the South America Affinity Group (SAAG 2026), show similar results.

For hybrid products such as CHIRPS, the number and distribution of stations used in the analysis can also impact the quality of the dataset. In regions where station availability decreases during recent decades (**Figure 1a**), precipitation estimates may become increasingly dependent on climatological information and satellite retrievals. Such changes can potentially generate artificial drying or wetting signals (e.g., Costa et al. 2019; Sapucci et al. 2022).

Seasonal/Monthly Climatologies: **Figure 3**, provides an intercomparison of the climatological seasonal cycle of precipitation across seven standard South America regions defined by the Intergovernmental Panel on Climate Change (IPCC 2023). Regions spanning the Andes, which are characterized by highly complex topography, exhibit a degradation in multi-dataset consensus (**Figure 3a,e**). Over tropical Northwestern South America (NWS; **Figure 3a**), precipitation exhibits a bimodal seasonal pattern, with dual maxima

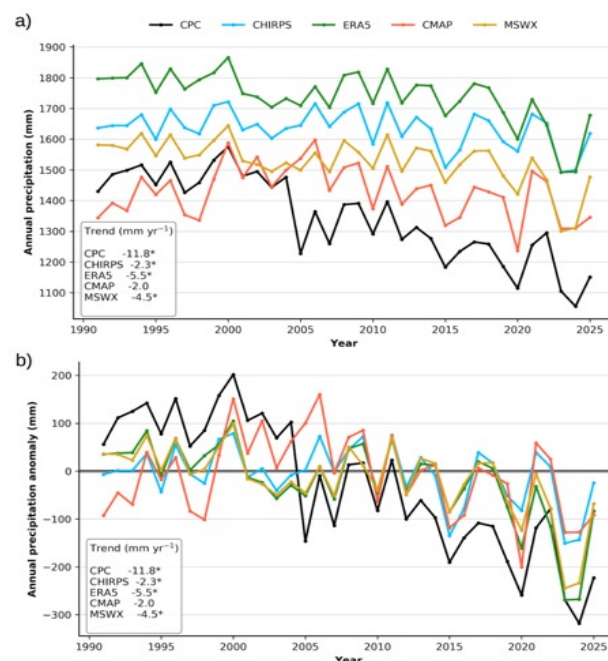


Figure 2 (a) Annual precipitation (mm year⁻¹) and (b) anomalies averaged over all land grid cells in continental South America derived from different datasets for the period 1991–2025. (a) annual mean precipitation and (b) annual anomalies. Significant trends obtained with Wald test at 5% of significance are indicated by * in the figure.

occurring during the transition seasons of April–May and October–November. Southwestern South America (SWS, **Figure 3e**) is characterized by a winter-precipitation regime peaking in June–July. In both regions, a spread is observed among the datasets, with ERA5 being the wettest and CPC and CMAP the driest. Over NWS, in the first peak of precipitation, the difference between the wettest and driest datasets can reach 150 mm month⁻¹ (**Figure 3a**). Southern South America (SSA) is also a region of large spread among datasets (**Figure 3g**). This region features a generally flat annual cycle with subdued seasonal variability. However, the multi-dataset spread is wide: ERA5 shows values between 80 and 100 mm month⁻¹ year-round, whereas CPC and CMAP have values ranging between 25 and 45 mm month⁻¹.

The three regions exhibiting the greatest uncertainty among the datasets (NWS, SWS, and SSA) have low density of stations (**Figure 1b**). Concurrently, these areas encompass highly complex and rugged topography, which inherently demands a denser monitoring network to accurately capture regional climatic variations.

Moving into Northern South America (NSA, **Figure 3b**), the annual cycle is also a unimodal, with a seasonality dictated by the Northern Hemisphere summer monsoon that peaks between May and June. While the datasets broadly agree on the phase and timing of the NSA rainy season, a divergence in magnitude emerges during the peak months, where ERA5 and

CPC represent the upper and lower envelopes of uncertainty, respectively. In contrast, Northeast South America (NES; **Figure 3c**), the South American Monsoon region (SAM; **Figure 3d**), and Southeastern South America (SES; **Figure 3f**) display the highest level of inter-dataset consensus. Over NES, all datasets tightly align to depict a sharp unimodal cycle peaking in January-March, followed by a dry season from June to October (**Figure 3c**). Similarly, SAM reflects a robust monsoonal regime characterized by a well-defined wet season spanning October to March, with a peak in December-March. In SES (**Figure 3f**), precipitation is minimum in August and MSWX is slightly dryer than the other datasets.

The minimal spread among the datasets across the NES and SES regions (with the exception of SAM) is likely a positive consequence of the higher density of stations in these areas, as demonstrated in **Figure 1b**. Conversely, the pronounced spread observed in NWS, SWS, and SSA highlights the ongoing challenges that different precipitation products face when resolving rainfall over complex terrain, high-latitude zones, and data-sparse regions. Furthermore, the low station density in these specific domains appears to artificially suppress precipitation estimates, particularly within the CPC and CMAP datasets, pulling the continental-scale averages downward when South America is considered as a whole (**Figures 2 and 3h**).

For climatological analyses, datasets such as CHIRPS and ERA5 generally provide useful information because spatial and temporal averaging tends to reduce random errors. Several studies have shown that CHIRPS performs particularly well in reproducing monthly precipitation patterns and seasonal variability (Rivera et al. 2018; Costa et al. 2019; López-Bermeo et al. 2022; Benítez et al. 2024). However, its performance tends to deteriorate at daily timescales, especially for localized extreme events (López-Bermeo et al. 2022). Its long temporal coverage beginning in 1981 also makes it attractive for climate applications (Funk et al. 2015). Overall, users should recognize that agreement among products does not necessarily imply their accuracy in more refined time scales (for instance, hourly precipitation). Significant differences can still occur in regions with sparse observational networks.

Daily Precipitation and Extreme Events: To address the uncertainty of the datasets at daily temporal scale, **Figures 4 and 5** show, respectively, a relative frequency distribution and probability density function (PDF) for days with precipitation (dry days are not included in the analysis). CMAP is available only at monthly or pentadal resolution and, therefore, it is omitted in the analysis.

Figure 4 indicates that low-intensity precipitation ($> 0 - 5 \text{ mm day}^{-1}$) represents the vast majority of rainy days across South America, accounting for over 65% of the total relative frequency in all datasets. Within the

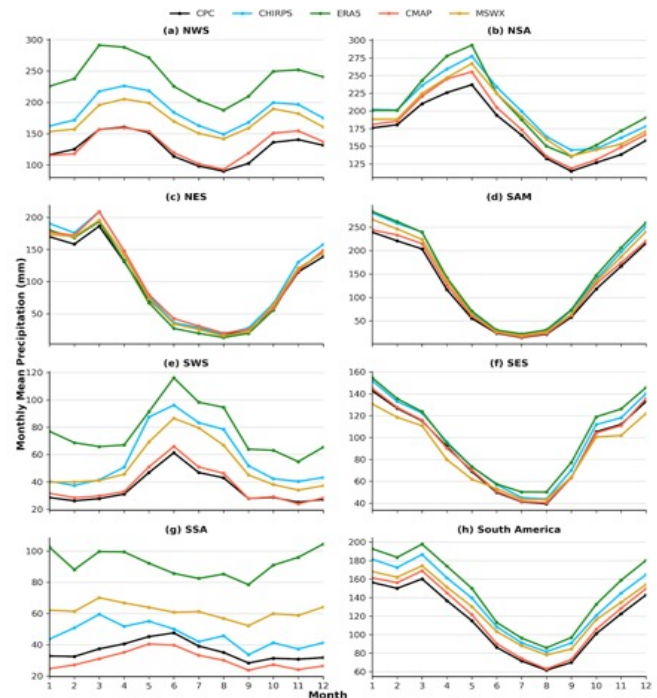


Figure 3 Climatological annual cycle of precipitation (mm month^{-1}) spatially averaged over land grid points across (a-g) seven IPCC regions and across (h) South America as a whole, derived from different datasets for the period 1991–2025. The seven regions are (a) NWS, (b) NSA, (c) NES, (d) SAM, (e) SWS, (f) SES, and (g) SSA.

higher intensity intervals ($> 20 \text{ mm day}^{-1}$), CPC exhibits the highest relative frequency, followed closely by CHIRPS and ERA5.

In the PDF (**Figure 5**), while all four datasets exhibit a coherent, steeply declining exponential decay from > 0 to 25 mm day^{-1} , substantial divergence and noise emerge as daily precipitation shifts into heavy and extreme regimes ($> 100 \text{ mm day}^{-1}$).

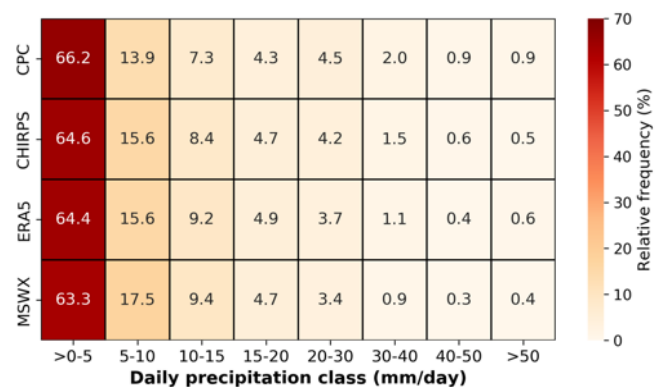


Figure 4 Relative frequency distribution (%) for rainy days considering all of South America.

Between 25 and 90 mm day^{-1} , CPC maintains a higher probability density compared to the other three gridded products. However, beyond 100 mm day^{-1} , a critical crossover occurs: ERA5 begins to consistently display the heaviest tail, showing a higher probability density for extreme precipitation events up to 250 mm day^{-1} . This behavior reflects the known reanalysis characteristic where convective parameterizations or

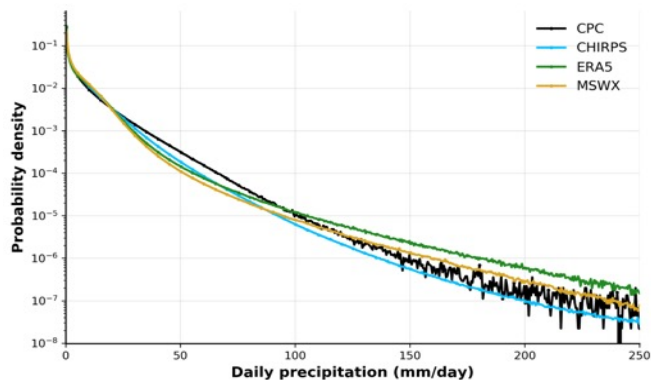


Figure 5 Probability density function for rainy days considering all of South America.

grid-scale dynamics over land can generate persistent heavy rainfall structures. In contrast, CHIRPS acts as the lower bound of the continuous distribution, exhibiting the sharpest and most conservative decay in probability density within the 100 and 250 mm day⁻¹ range. MSWX PDF curve remains intermediate between ERA5 and CHIRPS. Finally, the station-only CPC dataset exhibits significant noise for values exceeding 150 mm day⁻¹, which is a mathematical artifact of fewer physical stations per grid point capturing these localized, highly sporadic extreme values over the continent.

At daily timescales, differences among datasets arise not only from observational coverage but also from the ability of retrieval algorithms and interpolation techniques to represent the intensity, location, and timing of rainfall events. Extreme rainfall events often occur at spatial scales smaller than the resolution of many observational products. Satellite retrieval algorithms may underestimate intense convective systems, while interpolation methods may smooth localized precipitation maxima. Reanalysis products provide spatially complete fields but generate precipitation through model parameterizations that do not always reproduce observed daily rainfall distributions.

Several studies over South America have shown that the skill of precipitation datasets generally decreases as temporal resolution increases, with larger uncertainties in the representation of heavy rainfall events and extreme precipitation indices (e.g., Rivera et al. 2018; Olmo and Bettolli 2021; Sapucci et al. 2022; Benítez et al. 2024).

Products that perform well at monthly timescales may therefore exhibit substantial limitations for studies of daily extremes. This distinction is especially important because precipitation extremes are increasingly used to evaluate climate simulation.

Researchers should avoid assuming that a dataset validated at monthly scales is equally reliable for analyses of daily precipitation extremes. Hence, it

is important to perform a more detailed analysis of the datasets including precipitation frequency distributions, wet-day occurrence, intensity percentiles, and extreme-event statistics. Using multiple observational datasets is strongly recommended to quantify observational uncertainty and avoid overconfidence in conclusions derived from a single product.

Hourly Precipitation: Hourly precipitation represents one of the most challenging time scales to observe, since errors in the timing of precipitation may affect the understanding of the diurnal cycle of this variable. The diurnal cycle of precipitation is particularly relevant for evaluating convection-permitting simulations, since these models are designed to explicitly represent convective processes and their temporal evolution (Coppola et al. 2025; da Rocha et al. 2025).

The availability of reliable hourly precipitation datasets remains limited. Among the products considered in this study (**Table 1**), only ERA5 and the 3-hourly version of MSWX provide continuous sub-daily information suitable for continental-scale analyses. However, these products are not direct observations. ERA5 precipitation is strongly influenced by model physics and data assimilation procedures, while MSWX inherits uncertainties from both reanalysis inputs and the bias-correction methodology used in its construction.

Figure 6 illustrates the mean diurnal cycle of precipitation over SAM and SES derived from ERA5 and MSWX. The whole continent is not evaluated in just one graphic because the diurnal cycle is dependent on the climate controls of a region. The SAM and SES regions were selected because they are characterized by monsoon-like precipitation regimes, with deep convection playing a dominant role, particularly during the austral summer.

In both regions (**Figure 6**), ERA5 and MSWX consistently reproduce the typical continental diurnal cycle, with precipitation gradually increasing from the early morning hours, reaching a maximum at 1800 UTC (approximately 1500 local time), and then decreasing during the evening. This behavior reflects the daytime growth of the planetary boundary layer and the development of convective instability driven by solar heating, which promotes the formation of deep convective clouds during the afternoon. The timing of the precipitation maximum agrees well with previous studies over South America (e.g., Reboita et al. 2016).

Although the two datasets exhibit a very similar temporal evolution, ERA5 systematically produces slightly higher precipitation amounts than MSWX throughout the day in both regions, highlighting the uncertainties associated with different datasets.

4. Exemplifying the Problem

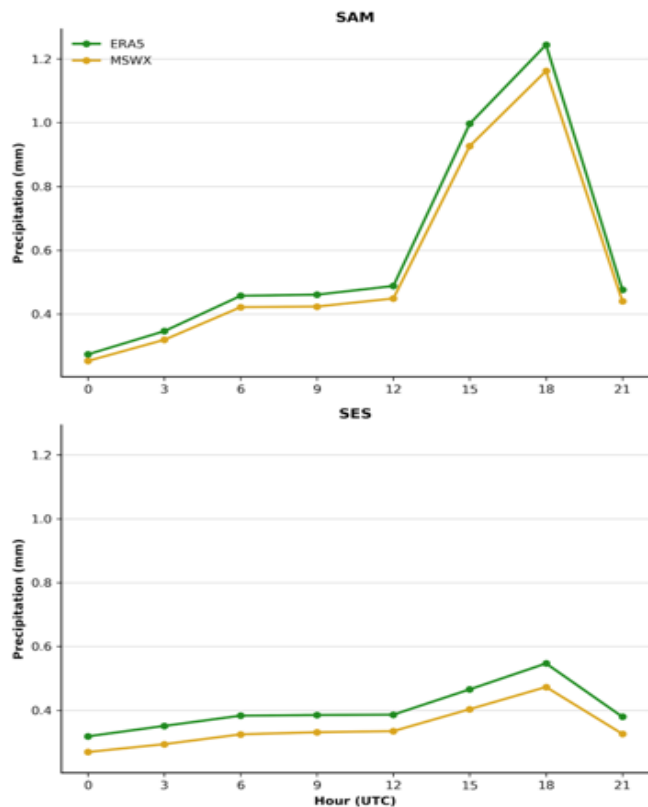


Figure 6 Diurnal cycle of precipitation (mm) for the period 1991-2025 over SAM and SES IPCC regions obtained from ERA5 (green) and MSWX (orange).

The uncertainties embedded within these datasets become an even more critical issue when evaluating the performance of numerical models. In some instances, a model may be erroneously categorized as having low predictive skill when, in reality, the discrepancy stems from observational uncertainties. These uncertainties are exemplified in **Figures 7**, which present the seasonal precipitation anomalies across South America for the austral summer (DJF) and autumn (MAM) of 2026 from ERA5, CHIRPS, CPC, MSWX and CMAP.

In a broader view of **Figure 7**, DJF 25/26 was characterized by positive precipitation anomalies extending from northwestern South America to southern Amazonia and parts of southeastern Brazil. Negative anomalies predominated over the remaining regions. This spatial pattern is more consistent among ERA5, CHIRPS, and MSWX, whereas CMAP and CPC show the positive anomalies confined farther to the northwest. In addition, CPC indicates much drier conditions (anomalies below -300 mm) over central and eastern Brazil, while CMAP, owing to its coarse spatial resolution, produces smoother anomaly patterns.

In MAM 2026 (**Figure 8**), two centers of positive precipitation anomalies are evident: one over Peru and another over northern South America. These are separated by a band of negative anomalies extending from northwestern South America across the Amazon. Once again, this pattern is more consistent among ERA5, CHIRPS, and MSWX, although CHIRPS

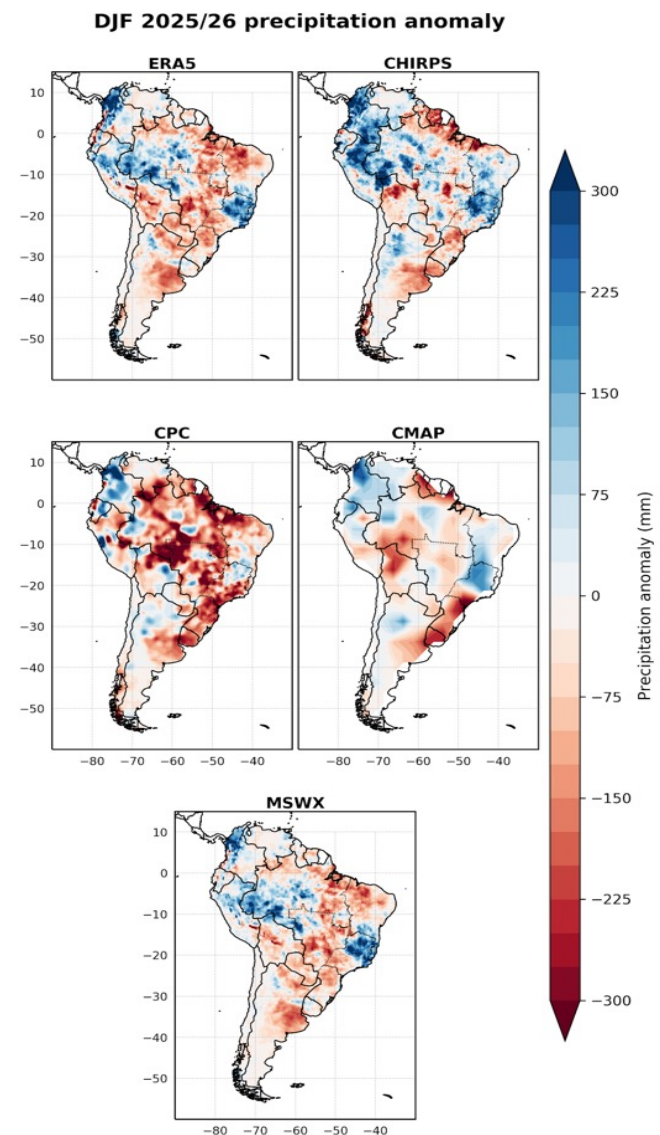


Figure 7 DJF 2025/26 precipitation anomalies (mm) over South America.

indicates near-normal to positive anomalies over most of Brazil, whereas ERA5 and MSWX show predominantly negative anomalies. In contrast, CPC and CMAP depict dry anomalies over these same regions. In the CPC dataset, the interpolation process is evident, as circular regions of more intense anomalies appear across the continent.

These differences in the spatial distribution and magnitude of precipitation anomalies highlight why selecting a single reference dataset as the "ground truth" can introduce bias into numerical model evaluations. For example, a seasonal prediction model forecasting wet anomalies over Peru and western Amazonia during MAM 2026 would achieve high skill scores when verified against ERA5, CHIRPS, or MSWX, but substantially lower scores when evaluated against CPC or CMAP. These continental-scale discrepancies demonstrate that structural uncertainty among precipitation datasets is a critical factor that must be considered before drawing conclusions about model predictive skill.

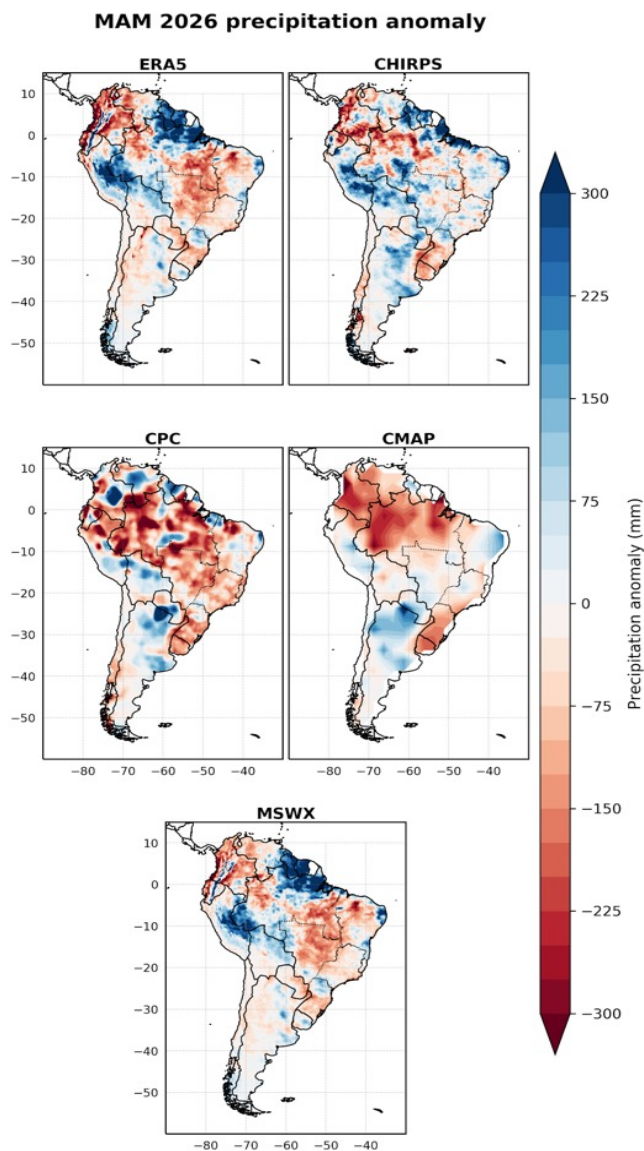


Figure 8 MAM 2026 precipitation anomalies (mm) over South America.

4. Final Comments

This study demonstrates that uncertainties among the most widely used precipitation datasets over South America are not limited to absolute rainfall amounts but also affect the representation of the annual cycle, long-term trends, seasonal variability, and sub-daily characteristics. These differences may be comparable to, or even larger than, the climate signals that many studies seek to detect. Consequently, conclusions regarding precipitation variability and change may depend substantially on the dataset selected.

Rather than attempting to identify a single best product, this study argues that dataset suitability depends strongly on the scientific application, temporal scale, spatial scale, and observational constraints.

An important implication of this study is that reducing precipitation uncertainty requires continued investment in observations, not only in the development of

improved satellite retrievals and hybrid products but also in the maintenance and expansion of long-term surface rain-gauge networks. Ground observations remain essential both for the calibration and validation of satellite estimates, for the construction of reliable long-term climate records, and model validation. As observing systems evolve, preserving the continuity and quality of these measurements will be critical for improving future precipitation datasets and for increasing confidence in assessments of climate variability and change across South America.

Overall, the principal recommendation emerging from this work is that precipitation dataset uncertainty should be treated as an integral component of scientific analyses rather than as a secondary consideration. Whenever feasible, scientific conclusions should be evaluated across multiple observational products, particularly in regions and timescales where observational uncertainty is comparable to the climate signal itself.

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Southern Hemisphere Extratropical Cyclone Response to Solar Radiation Modification Techniques: Marine Cloud Brightening and Stratospheric Aerosol Injection

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1. Introduction

Extratropical cyclones are the dominant weather systems in the mid-latitudes and constitute a major source of weather and climate variability, influencing precipitation, temperature, and wind patterns over large regions (Schultz et al. 2019).

Projections of extratropical cyclones in the Southern Hemisphere under the Intergovernmental Panel on Climate Change (IPCC 2023) warming scenarios indicate a decrease in the frequency of these systems accompanied by an increase in their intensity (Reboita et al. 2022, 2024). Given that global warming is unlikely to be sufficiently mitigated in the coming decades, increasing attention has been devoted to climate intervention strategies aimed at reducing global temperatures (Robock 2020). One such approach is Solar Radiation Modification (SRM), which includes three main categories: Cirrus Cloud Thinning (CCT), Stratospheric Aerosol Injection (SAI), and Marine Cloud Brightening (MCB) (Redmond Roche et al. 2026).

CCT seeks to reduce the coverage or optical thickness of high cirrus clouds, allowing more longwave radiation to escape to space and thereby cooling the climate system (Mitchell and Finnegan 2009). SAI refers to the injection of reflective aerosol particles into the stratosphere to increase planetary albedo and reduce incoming solar radiation (Kravitz 2013). MCB, on the other hand, involves injecting sea-salt aerosols into marine clouds to increase the number of cloud condensation nuclei. This produces more numerous but smaller cloud droplets, reducing precipitation efficiency and increasing cloud reflectivity (albedo). The brighter, longer-lived clouds reflect more sunlight back to space, potentially offsetting some warming caused by greenhouse gases (Poulin 2026). Due to the short atmospheric lifetime of sea salt aerosol, their resulting radiative forcing is regional by nature (Hirasawa et al. 2026a; Doherty et al. 2026).

SAI is the approach with experiments provided by different international projects (ARISE, GLENS and GeoMIP; see Reboita et al. 2024). For instance, the ARISE-SAI-1.5 experiment (Richter et al. 2022) uses the SSP2-4.5 scenario and stabilizes global warming at

1.5°C above pre-industrial levels. On the other hand, MCB experiments are scarcer. In one of the first global experiments for MCB, the injection of sea-salt aerosols (iSSA) occurred in subtropical regions (causing strong climate anomalies similar to the La Niña patterns). The latest MCB experiment released to the scientific community is the G6-1.5K-MCB (Hirasawa et al. 2026b), which was designed to limit global average temperature rise to approximately 1.5°C above pre-industrial levels. It uses the SSP2-4.5 scenario as a baseline, and injects iSSA across five mid-latitude oceanic regions (2 in the Northern Hemisphere and 3 in the Southern Hemisphere). This strategy generates a spatially more uniform cooling pattern than the first mentioned experiment and counterbalances greenhouse gas-induced warming without exacerbating warming in specific regions or severely destabilizing tropical circulation.

Using SAI scenarios, Reboita et al. (2024) showed that the frequency and intensity of Southern Hemisphere extratropical cyclones become more similar to those observed in the present climate than under warming scenarios without intervention. Furthermore, Ribeiro et al. (2025) found that, under SAI, extratropical cyclones produce less precipitation and weaker winds compared to high-emission scenarios without climate intervention. Consequently, the relative contribution of these cyclones to regional precipitation totals and wind intensity decreases from the near to the far future under SAI, suggesting that this intervention may mitigate some of the warming-induced intensification of these weather systems.

In contrast, little is currently known about the impacts of MCB implementation in the mid-latitudes on extratropical cyclones. Most studies focus on tipping elements and indicate that MCB can reduce the risk of coral reef heat stress and weakening of the Atlantic Meridional Overturning Circulation. However, its effectiveness is highly dependent on the deployment region, and in some areas MCB may amplify greenhouse gas-induced impacts, highlighting the need for careful assessment of potential regional climate effects (Hirasawa et al. 2023).

Building on the previous discussion, this study

investigates the response of Southern Hemisphere extratropical cyclones to global warming under scenarios with and without MCB (G6-1.5K-MCB), and compares these responses with those under a SAI scenario that achieves a comparable temperature reduction (ARISE-SAI-1.5). The analysis focuses on projected changes in cyclone frequency, intensity, and spatial distribution over the period 2035–2069.

2. Methodology

Study Area: The study area is the Southern Hemisphere from 20°S to 90°S.

Data: The study uses 6-hourly mean sea level pressure (MSLP) from three members of three Community Earth System Model version 2.1 (CESM2.1) experiments spanning 2035–2069 (the last simulated year available for the MCB experiment), with a horizontal resolution of 1.25° longitude × 0.9° latitude. The experiments are (1) baseline climate condition, which is the SSP2-4.5 scenario from CMIP6 using CESM; (2) G6-1.5K-MCB (Hirasawa et al. 2026b), which uses the Community Atmosphere Model version 6 (CAM6); and (3) the ARISE-SAI-1.5 (Richter et al. 2022), which employs the Whole Atmosphere Community Climate Model version 6 (WACCM6) and is the SAI experiment. The SAI experiment was included to enable a comparison of the climatic impacts associated with the MCB approach. MSLP fields were bilinearly interpolated to a resolution of 1.5° × 1.5° (lat, lon) and used to identify and characterize extratropical cyclones.

Cyclone Identification, Tracking, and Analysis: Cyclones were identified and tracked using the objective numerical scheme developed by Murray and Simmonds (1991). The tracking algorithm detects systems based on local maxima of the pressure Laplacian ($\nabla^2 p$), which provides a robust measure of cyclone intensity and circulation structure. The lifecycle of each cyclone was determined from the number of time steps during which the system was identified by the algorithm.

To assess the effects of the MCB and SAI approaches on cyclone activity, annual climatological metrics were calculated and compared across scenarios.

3. Results

Figure 1 shows the projected time-evolution of extratropical cyclone characteristics under SSP2-4.5, MCB and SAI scenarios. Regarding cyclone frequency (Figure 1a), both climate intervention scenarios project a higher number of cyclones than SSP2-4.5. In terms of intensity, the higher central pressure at cyclogenesis (Figure 1b) and the higher minimum central pressure reached during the cyclone lifecycle (Figure 1c) indicate that cyclones are weaker under the MCB and

SAI scenarios than under SSP2-4.5. These differences are statistically significant at the 95% confidence level based on Student's *t*-test. Changes in travel distance (Figure 1d), cyclone lifetime (Figure 1e), and mean velocity (Figure 1f) are comparatively small, indicating limited sensitivity of these characteristics to the climate scenario considered.

The mean annual number of cyclones is 558, 571, and 569 in the SSP2-4.5, SAI, and MCB scenarios, respectively. Relative to SSP2-4.5, cyclone frequency increases by 2.3% in the SAI scenario and 2.0% in the MCB scenario, resulting in a climatology that more closely resembles present-day conditions. The annual cycle of extratropical cyclone frequency in all three scenarios follows the expected climatological pattern, with maximum cyclone activity occurring during austral autumn and winter, when enhanced baroclinicity favors cyclogenesis, and minimum activity occurring during austral summer (Figure 2).

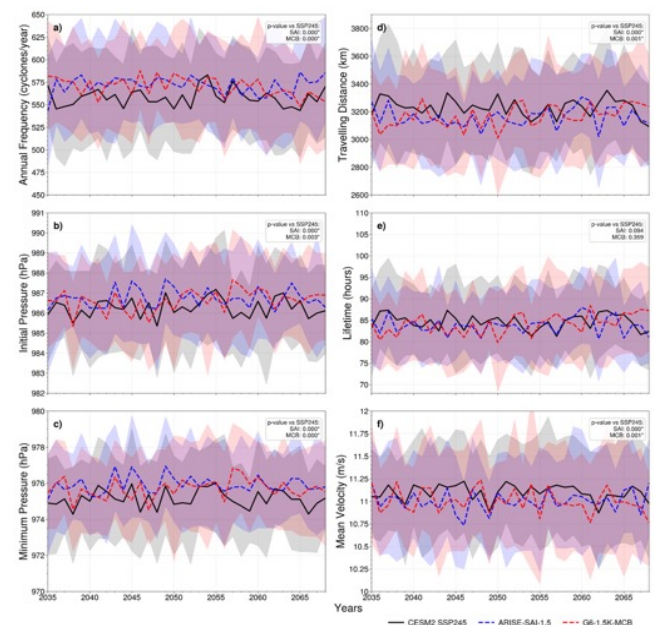


Figure 1. Main characteristics of Southern Hemisphere extratropical cyclones under the three-member ensembles of the SSP2-4.5 (solid black line), SAI (dashed blue line), and MCB (dashed red line) experiments during 2035–2069. The shaded areas indicate the spread among ensemble members, defined by the minimum and maximum values obtained across the three members of each experiment. The characteristics shown are: (a) annual frequency (number of cyclones per year), (b) central pressure at cyclogenesis (hPa), (c) minimum central pressure during the cyclone lifecycle (hPa), (d) travel distance (km), (e) lifetime (hours), and (f) mean moving speed (m s^{-1}). Statistically significant differences between SSP2-4.5 and the climate intervention scenarios at the 95% confidence level, based on Student's *t*-test, are indicated by an asterisk (*) in the legend.

Spatial differences in cyclone track density between the SAI and MCB experiments and the SSP2-4.5 scenario, evaluated for three time slices (2040–2049, 2050–2059, and 2060–2069), indicate an increase in cyclone frequency across large portions of the

Southern Hemisphere, particularly over the Pacific Ocean and within the midlatitude band between approximately 50°S and 60°S. In contrast, decreases in cyclone frequency are projected in regions closer to Antarctica (Figure 3).

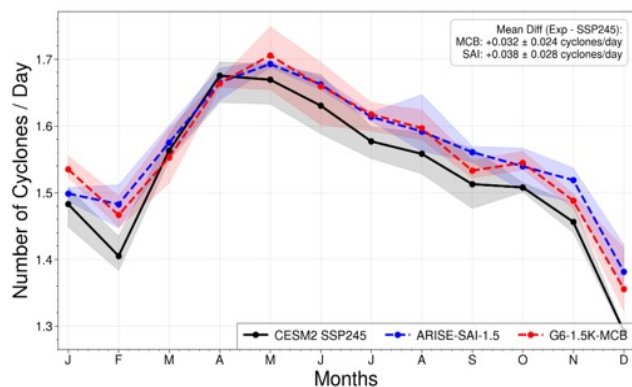


Figure 2. Annual cycle of extratropical cyclones (monthly number of systems divided by the number of days in each month), during 2035–2069, under the three-member ensembles of the SSP2-4.5 (solid black line), SAI (dashed blue line), and MCB (dashed red line) scenarios. The shaded areas indicate the spread among ensemble members, defined by the minimum and maximum values obtained across the three members of each experiment. The bias and standard deviation of the SAI and MCB scenarios relative to SSP2-4.5 are shown in the figure legend.

To assess the degree of similarity between the spatial patterns of cyclone track density in the SAI and MCB experiments relative to SSP2-4.5, spatial correlations were calculated for each time slice. The resulting correlations are 0.43, 0.47, and 0.49 for the first, second, and third time slices, respectively (Figure 3). These positive correlations indicate a moderate agreement between the spatial responses of the two approaches, despite differences in the exact location and trajectories of individual cyclones. The increasing correlation over time further suggests a growing convergence in the large-scale cyclone distribution changes simulated by the SAI and MCB experiments.

4. Conclusions

The results indicate that both baseline and climate intervention scenarios preserve the historical annual cycle of extratropical cyclones, with peak cyclogenetic activity occurring during austral autumn and winter. However, global warming is projected to reduce cyclone frequency while increasing cyclone intensity, resulting in fewer but stronger systems. Climate intervention strategies, SAI and MCB, partially mitigate these changes by maintaining a slightly higher frequency of weaker cyclones. Structural and kinematic properties, including cyclone lifetime, travel distance, and mean velocity, exhibit relatively small changes across all scenarios. The spatial distribution of cyclone track density is also quite similar between the MCB and SAI experiments.

Overall, the results suggest that MCB and SAI exert similar influences on Southern Hemisphere

extratropical cyclones, moving their climatological characteristics closer to those of the present-day climate than those projected under SSP2-4.5. Given the comparable cyclone responses identified here, future assessments should focus on differences in implementation feasibility, governance, risks, uncertainties, and broader climatic impacts when evaluating the relative merits of these two climate intervention approaches.

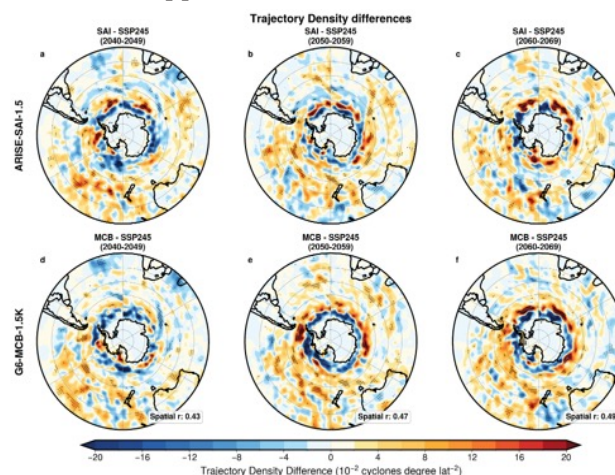


Figure 3. Differences in cyclone trajectory density (10^{-2} cyclone degrees lat^{-2}) between the SSP2-4.5 scenario and the SAI (top row) and MCB (bottom row) experiments for the decades 2040–2049 (left column), 2050–2059 (middle column), and 2060–2069 (right column). Areas enclosed by dashed contours indicate statistically significant differences at the 95% confidence level ($\alpha = 0.05$). The spatial correlation between the differences obtained for SAI and MCB is shown at the bottom of the figure.

Acknowledgments

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