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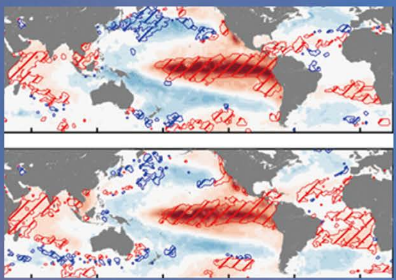
# CLIVAR Exchanges



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| 0.67 | 0.63 | 0.76 | 0.71 |
| 0.57 | 0.52 | 0.50 | 0.51 |
| 0.72 | 0.69 | 0.77 | 0.74 |
| 0.70 | 0.61 | 0.63 | 0.66 |
| 0.69 | 0.64 | 0.69 | 0.64 |
| 0.69 | 0.63 | 0.71 | 0.71 |
| 0.67 | 0.65 | 0.73 | 0.72 |
| 0.67 | 0.62 | 0.68 | 0.64 |
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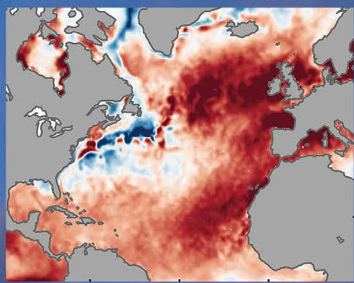

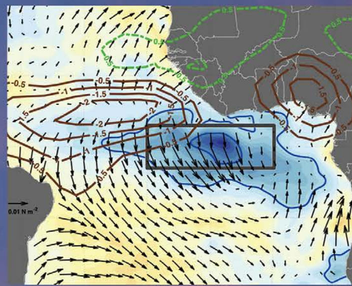

## Confronting the Future

*Emerging Anomalies and the Need for Building Scientific Capabilities*

30TH CLIVAR Anniversary

No.84, December 2025

CLIVAR Exchanges 84 No.84, December 2025

WCRP
World Climate Research Programme

CLIVAR (Climate and Ocean: Variability Predictability and Change) is a core project of the World Climate Research Programme focusing on ocean-atmosphere

**Cover image** credit: Dr. Anna-Lena Deppenmeier, Member of CLIVAR Pacific Region Panel.

A view of the Tropical Pacific Ocean during transit south on the "Mixing belOw Tropical Instability waVEs" (MOTIVE) 2025 cruise led by University of Washington Applied Physics Laboratory and Scripps Institution of Oceanography. Photo supplied by Anna-Lena Deppenmeier who was part of the crew going from Hawaii to Tahiti aboard the Sikuliaq to pick up three moorings around 140°W that were deployed in 2024, and to profile across tropical instability wave fronts to investigate the associated mixing.

# Editor’s message

2025 has flown by. It marked CLIVAR’s 30th anniversary, celebrated by the organisation of the Pan-CLIVAR Meeting last September. This once-in-a-decade event is naturally utilised for initiating the formulation of decadal CLIVAR science plan and implementation strategy. The second Pan-CLIVAR Meeting recently held in Bali, Indonesia also served to engage scientists and stakeholders in southeast Asia. It took nearly 2 years of planning, and a ton of perseverance given the challenges that 2025 presented us with. The event completed successfully (see page 35 for event rundown), thanks to the efforts of the organising committees, the Indonesian hosts, volunteers, and all the participants, with the support of WCRP, WMO, and sponsors.

This current issue 84 is inspired by Pan-CLIVAR 2025 visions towards building capabilities in observations, modeling, research, and prediction, to prepare for future climate variability in the backdrop of long-term changes (see Editorial on the next page). I thank Antonietta Capotondi and Thea Turkington for editing the scientific articles with me, and the article contributors, many of whom are members of Monsoons, Climate Dynamics, and Atlantic panels.

The next Exchanges issue is expected to contain articles on Pan-CLIVAR 2025 achievements with reflections and aspirations as CLIVAR marches forward beyond 30 years. In this current issue, Juliet Hermes shares her perspective on 30th anniversary and her inspiring and rewarding journey in CLIVAR (page 41), reminding us that we are a family working towards a common mission. In moving forward, we shall also remember those who have inspired us and contributed to scientific advances and the success of CLIVAR. Alexander Polonsky kindly writes on page 42 a memorial tribute to Prof. Stefan Hastenrath, a leading scientist whose works contributed towards the first CLIVAR Science Plan released in August 1995. We repost on page 44 an obituary of Dr. Howard Cattle who served as ICPO director in 2002-2010 when the project office was hosted by the National Oceanography Centre, Southampton, UK.

I can attest based on just 2 years of experience that running the ICPO is a tough but rewarding job. It has been a privilege and honour for me to serve CLIVAR in this capacity, but regrettably I must step down. I would like to thank the entire CLIVAR and WCRP communities and partners, particularly previous CLIVAR SSG Co-Chair Sonya Legg as well as WCRP secretariat Hindumathi Palanisamy and US CLIVAR Mike Patterson for the support and guidance especially during the first year when I was the only staff in the office. I am grateful for the unwavering support from Ocean University of China and Laoshan Laboratory that have co-hosted the ICPO since 2023, including their scientists and staff who have been very welcoming since day 1. I thank the International Monsoons Project Office (IMPO) and their director Rajagopal (who has recently retired) for supporting the CLIVAR/GEWEX Monsoons Panel.

Many institutions have hosted CLIVAR events, like the International Centre for Theoretical Physics, First Institute of Oceanography, Yonsei University, University of Hawaii, Australian Research Council Centres of Excellence for Climate Extremes and 21st Century Weather, just to mention a few, that hosted recent CLIVAR events. Such support is important to drive climate science forward towards the benefit of the environment and society we live in.

2026 will be an important and yet another busy year for CLIVAR. With the sunsetting of the research focus (RF) on Tropical Basin Interactions (TBI), a new RF is hoped to be established some time in the second half of the year. We will see more activities and new outcomes, as CLIVAR panels have recently formed, or are in the process of, establishing more working groups and task teams, like PRP’s PATAC and TP BGC-PIs, CDP’s TROPICS, OMDP’s regional ocean-climate projections, IORP’s QIndOOS, paleo, and coastal task teams. We also anticipate elevated scientific research arising from TBI RF and recently published CLIVAR-led community reviews on marine heatwaves, pantropical ocean observing system, ENSO conceptual model, among others. CLIVAR now holds regular webinars from various panels, the most recent of which is led by OMDP, with ENSO webinars starting in January 2026, providing a platform for scientific dissemination and collaborations.

Taking off from Pan-CLIVAR 2025, the SSG will take the lead in formulating the next CLIVAR Science Plan and Implementation Strategy. With a new logo to be fully adopted in January, CLIVAR will march on with renewed energy to confront future challenges.

Sincerely yours,

Agus Santoso
Director, International CLIVAR Project Office

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# Editorial: Confronting the Future – Emerging Anomalies and the Need for Building Scientific Capabilities

**Agus Santoso[1], Antonietta Capotondi[2], Thea Turkington[3]**

[1] International CLIVAR Project Office, Ocean University of China, Qingdao, China
[2] CIRES, University of Colorado Boulder, and NOAA Physical Sciences Laboratory, Boulder, CO, USA
[3] Centre for Climate Research Singapore, Meteorological Service Singapore, Singapore

We have completed the first quarter of the 21$^{st}$ century, which has been marked by record-breaking global temperatures and occurrences of extreme events around the world. This issue of CLIVAR Exchanges profiles some recent oceanic anomalies such as the severe North Atlantic marine heatwaves in 2023 (*Guinaldo et al.*) and an Atlantic Niña in 2025 (*Tuchen*), as well as efforts in understanding, monitoring, and predicting the climate (*Gunnarson et al.; Pradhan et al.; Ratna et al.; Drumond et al.*).

In boreal spring 2023, WCRP issued a press release of an assessment by the CLIVAR Marine Heatwaves in the Global Ocean Research Focus on the all-time high global ocean temperatures and their impacts, as 27% of the global ocean was in marine heatwave conditions (https://www.wcrp-climate.org/news/wcrp-news/2054-impacts-of-marine-heat-waves). The North Atlantic Ocean experienced especially severe marine heatwaves as highlighted in this Exchanges issue by *Guinaldo, England*, and *Li* who profiled two independent studies investigating the processes behind this record-breaking event. They conclude that the event was unprecedented and unusual in the observational record. While driven by internal variability, anthropogenic warming was essential for the event to achieve the observed severity, consistent with climate models projections. In particular, the record intensity cannot be solely explained by atmospheric anomalies, but requires contribution from surface mixed layer shoaling and increased ocean stratification, highlighting the fundamental role of the changing oceans and their interactions with the atmosphere in producing extreme events.

A prominent source of internal variability and driver of marine heatwaves on a global scale is the El Niño Southern Oscillation (ENSO) which is sourced in the tropical Pacific Ocean. El Niño tends to increase sea surface temperature (SST) over vast regions across the globe especially towards and following the event maturity. The year 2023 saw the development of a strong El Niño, concurrent with the North Atlantic warming. To isolate processes that are related and unrelated to ENSO, the ENSO signals first need to be removed from the time series prior to analysis as demonstrated by *Gunnarson, Wang, et al*. They evaluated different methods for signal removal, and using their best identified method, they quantified ENSO contribution to global SST variability, thus also offering insights into the role of ENSO in the recent marine heatwaves.

ENSO impacts many aspects of climate other than marine heatwaves. For example, it can affect rainfall, which society depends upon for water resources, while at the same time it can also be a source for disasters, such as floods, landslides, waterborne diseases, and (for the lack of it) drought and forest fires. Ability to model and predict ENSO events, as well as their phase transitions, is crucial for society in mitigating risks and managing resources, particularly in regions that are strongly affected by ENSO like India. *Pradhan, Rao, et al.* evaluate the performance of several climate models used in operational forecasting systems in predicting the Indian summer monsoon rainfall and ENSO. The higher models' skill in predicting ENSO than the monsoon rainfall and the fact that ENSO is a driver of monsoon rainfall variability suggests that further improvement in ENSO simulations could lead to better prediction of monsoon variability. On the other hand, *Ratna, Takle, et al*. evaluate the performance of the Indian coupled forecasting system in simulating and predicting ENSO phase transitions. They found that the model performs better in predicting the timing of El Niño-to-neutral and neutral-to-La Niña transitions than the converse.

Climate teleconnection indices, such as the widely used Niño3.4 index, are typically utilised by forecasters to explain and validate their predictions. Such indices can be accessed from many operational forecast agencies around the world. However, the use of varying datasets and climatological baseline periods across these sources makes it challenging to systematically monitor, understand, and evaluate prediction skill of various processes. *Drumond, de Oliveira Nogueira, et al*. present an online tool that outputs various teleconnection indices (e.g., Arctic Oscillation index, Dipole Mode Index) computed based on a standardised baseline period and datasets. This online tool provides a description of the data sources and methodology for the calculation, which would be convenient for the community to use, to keep up with emerging phenomena.

An indispensable element for climate monitoring, forecasting, and research is ocean-atmosphere observations in all ocean basins. This need has become even more critical as the world enters uncharted territories under increasing greenhouse warming with a more frequent emergence of extreme climate events. For instance, as described by *Philip Tuchen* in this issue, an Atlantic Niña was captured by the tropical Atlantic PIRATA moored buoys in boreal summer this year. The Atlantic equatorial cold anomaly, not seen since 2013 and the strongest Atlantic Niña since 1992, adds to the increased variability in the region which experienced an Atlantic Niño in 2021. While the underpinning processes are not yet understood, the detection of this year's La Niña demonstrates that in situ observations providing data in real time can allow a swift response from the community to address the situation, by stimulating research, enabling impact prediction, and anticipating the future.

Thus, as nature presents us with more extreme and unprecedented events, we need to further develop our capacity of observing, monitoring, modeling, understanding and predicting the climate. These developments require commitments to sustain these efforts, which may be facilitated by concerted international cooperations (such as that described by *Hermes et al*. in this issue on co-designing ocean observing for the tropics) and through the enhancement of capacity building activities, like the ICTP-CLIVAR Marine Heatwaves summer school in July 2023 (https://indico.ictp.it/event/10191/speakers) which inspired the work of *Gunnarson et al*., as well as several other summer school projects led by Early Career Ocean Professionals on the characteristics, causes and impacts of marine heatwaves in the global ocean.

# The 2023 North Atlantic marine heatwave: what, why, how, and what next?

**Thibault Guinaldo[1*], Matthew H. England[2, 3*], Zhi Li[2,3]**

[1] Météo-France, CNRS, Univ. Toulouse, CNRM, Toulouse, France.
[2] Centre for Marine Science and Innovation (CMSI), University of New South Wales, Sydney, NSW, Australia
[3] ARC Australian Centre for Excellence in Antarctic Science, University of New South Wales, Sydney, NSW, Australia
*Correspondence: thibault.guinaldo@meteo.fr; m.england@unsw.edu.au

## 1.Introduction

The year 2023 marked a turning point in public awareness of the ocean's role in climate change. Starting in spring, sea surface temperatures (SSTs) in the North Atlantic began to rise, reaching levels that place this event as the most extreme marine heatwave (MHW) ever observed in the basin (Fig. 1a). The observed record-breaking SST anomalies have, thus, been the subject of much analysis and discussion. Were these anomalies simply a random coincidence, or a sign that climate change is surging beyond what might be expected from projections? Two recent studies, one published in *Communications Earth & Environment* (Guinaldo et al. 2025) and another in Nature (England et al. 2025), provide answers to these pressing questions.

The North Atlantic Ocean circulation is a key component of the global ocean circulation with a significant influence on regional and large-scale climate. The tropical sector triggers the development of hurricanes, while the mid-latitudes regions regulate European and global climate.

- In winter, the North Atlantic Ocean influences the trajectory of storms affecting Europe and the severity of the cold season.
- In summer, the North Atlantic Ocean shapes the frequency of heatwaves, the availability of atmospheric moisture, and thus the balance between droughts and extreme rainfall.
- Globally, the North Atlantic basin plays a central role in redistributing heat from the tropics to the poles through the Atlantic Meridional Overturning Circulation (AMOC), a conveyor belt of ocean flow that controls the global energy balance.

In recent decades, the ocean southeast of Greenland has cooled in response to anthropogenic global warming, creating the so-called "cold blob" or "warming hole" (Caesar et al. 2018). In 2023, however, even this region recorded anomalies exceeding +2°C above the 1981–2010 average. Beginning in May, a basin-wide "horseshoe-shaped" pattern emerged, reminiscent of the leading mode of North Atlantic SST variability, but reaching unprecedented intensity. Local anomalies of +5°C were measured near the British Isles. SST anomalies across this horseshoe pattern further intensified during June (Fig. 1b), followed by record-breaking warming that developed in the northwest during July (Fig. 1c).

This phenomenon raised several important questions:

- What processes led to the emergence of such extreme heating conditions?
- Could such conditions have occurred by chance due to internal system variability?
- Was it a signal of accelerating global warming?
- Do climate models allow us to understand such an event?

The two studies published in 2025 address these issues by combining surface and subsurface observations with state-of-the-art numerical simulations.

## 2.Crucial ocean–atmosphere interactions

While the atmospheric conditions that led to the emergence of the MHW in May–July 2023 were a succession of a subset of summertime weather regimes, they were striking in their intensity. In particular, a record weakening of the tropical trade winds preceded a persistent high-pressure blocking system over the British Isles. Together, these anomalies produced excess heat on the ocean surface, which developed into a horseshoe-shaped configuration, the leading mode of SST variability in the North Atlantic Ocean.

The events followed this sequence:

i. **Weakened winds.** The start of the year was dominated by a negative phase of the North Atlantic Oscillation (NAO), when westerly winds across the mid-latitudes were weaker than usual. Then during June there was a pronounced weakening of the climatological anticyclone (Fig. 2a) and trade winds over the North Atlantic (Fig. 2b), leading to an

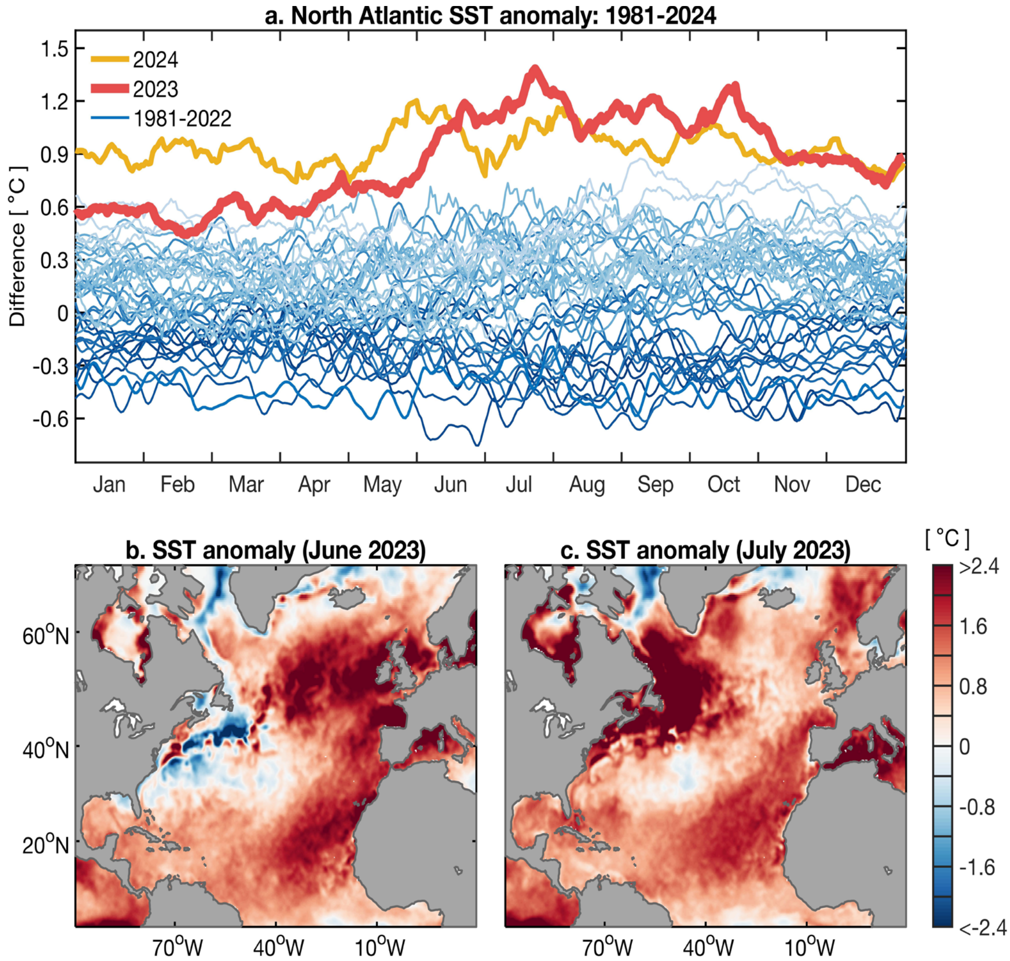


**Figure 1.** Observed record-breaking North Atlantic Sea Surface Temperature (SST) anomaly in 2023 and 2024. (a) Daily anomalies of SST with respect to the 1981-2010 mean from averaged over the North Atlantic. SST anomalies (°C) are averaged between the Equator and 60°N, with years indicated by colour shaded lines, from dark blues (earliest years) through to pale blues (most recent years), 2023 indicated in bold red, and 2024 bold yellow. Data are taken from ERA5. (b) and (c), Map of SST anomalies for June and July 2023, respectively.

intensification of tropical warming. These two successive atmospheric configurations were the main drivers of the emergence of the 2023 MHW that acted as a preconditioning of the surface.

**ii. Decreased cloud cover.** The reduction in trade winds led to a reduction in Saharan dust transport and also reduced cloud cover over the North Atlantic (Fig. 2c). Fewer clouds mean more solar radiation reaching the ocean surface and reinforcing the upper-ocean heat content (Fig. 2d). The development of a horseshoe pattern in SSTs influenced the cloud formation process through the SST-low cloud feedback (Yuan et al. 2016), resulting in persistently reduced cloud cover over the region during the summer.

**iii. Less heat sink by evaporation.** Another consequence of weaker winds is the reduced heat loss through evaporation (Fig. 2d), reinforcing the warming.

**iv. Reduced vertical mixing.** With weaker winds, the efficiency of vertical mixing and heat redistribution was reduced, resulting in heat accumulation in shallower surface mixed layers. In addition to the above factors, by June 2023 a high-pressure system became persistent over the British Isles, a classic blocking regime. This atmospheric pattern tends to suppress weather variability and maintain extreme SST forcing conditions (warm temperatures and weak winds). In this case, it created a heat dome over the northeastern Atlantic resulting in prolonged warming, with little possibility for cooling through wind-driven vertical mixing or advection.

## 3. Ocean stratification as a booster

Atmospheric anomalies alone cannot explain the record intensity of North Atlantic warming during 2023. The ocean's vertical structure played a critical amplifying role.

The ocean is naturally stratified: warm surface waters sit on top of colder, denser deep waters. Normally, winds and turbulence redistribute surface heat downward, preventing excessive surface heating. Global ocean warming, however, has altered this balance. Over the past decades, the upper North Atlantic Ocean has accumulated more and more heat, especially at the surface, strengthening ocean stratification. When the surface layer becomes more isolated from the deeper ocean, heat is accumulated at the surface for a longer time, amplifying the influence of atmospheric anomalies.

In 2023, stratification reached record levels across the North Atlantic in addition to above average air-sea flux anomalies. The mixed layer depth was remarkably shallow, barely 10 meters in places where it would typically be 20–40 meters deep in June and July. This made the ocean surface unusually sensitive to air-sea heat fluxes: even moderate reductions in wind and cloud cover translated into rapid heating. Once heat was trapped at the surface, with low wind speeds that heat remained there longer than in past decades.

Numerical models' sensitivity experiments confirmed this point: while incoming solar radiation was above average, the dominant drivers were the combination of mixed layer shoaling and the weakened winds. The key insight is that the ocean itself has changed. Warming caused by human activity has made the surface ocean layer more sensitive to atmospheric variability.

## 4. An unexpected event for the models?

Climate models participating in international projection projects (e.g. CMIP) show that an event like the 2023 heatwave is indeed possible, but only in the context of human-driven global warming.

- At the basin scale, average warming of this magnitude in the present climate has a return period of about once every 10 years. In today's climate, there is roughly a 10% chance each year of such an event occurring somewhere across the North Atlantic (Guinaldo et al. 2025).
- At the regional scale, however, the specific horseshoe-shaped pattern seen in 2023 remains far rarer, with a return period closer to 100 years.
- In terms of mixed layer depths, the shoaling observed during June-July 2023 would have a return period of around 1000 years in the absence of anthropogenic change (England et al. 2025). However, considering recent multi-decadal trends, summer mixed layers during 2023 were significantly shallower than the long-term trend, but not exceptional.

This means that while the 2023 event was unprecedented and unusual in the observational record, it was not outside the range projected by models. Indeed, the event fits within the framework of natural variability, supercharged by anthropogenic warming, just as climate models project. This result is critical: it reaffirms the reliability of climate models and emphasizes the importance of statistical framing in public communication of extreme events.

It also demonstrates that internal variability is supercharged by climate change:

- The atmospheric configuration in spring 2023 (negative NAO, weak trades, blocking regime) could occur naturally.
- However, in a cooler, pre-industrial climate, the same configuration would not have produced record-breaking anomalies.
- It was the background of anthropogenic warming and enhanced stratification that allowed natural variability to reach such extremes.

## 5. What about sulphur aerosols?

Another hypothesis raised in 2023 linked the event to international regulations that drastically reduced sulfur emissions from shipping, improving air quality but reducing the "parasol effect" of reflective aerosols (Yuan et al. 2024). While the rapid drop in sulphur aerosols appears to have had a signature in the 2023 warming at localised spatial scales, its contribution to the basin-average warming event was secondary to the processes described above (England et al. 2025). Moreover, these regulations and their impacts are already taken into account in Shared Socio-economic Pathways scenarios. In particular, the event was fully explicable through atmospheric variability interacting with a warmer, more stratified ocean (Guinaldo et al. 2025; England et al. 2025).

## 6. Conclusion

The North Atlantic marine heatwave of 2023 was the most intense ever observed, but the event can be explained by a combination of strong climate variability supercharged by ongoing global warming. The event emerged from a combination of internal atmospheric variability, leading to reduced winds and surface oceanic heat loss, acting on an upper-ocean that has undergone significant long-term trends due to human-driven warming and a shoaling stratification. Models are able to simulate such events, confirming that what was once considered rare is now plausible.

The key message is clear: the 2023 North Atlantic marine heatwave was due to a combination of climate variability made worse by preconditioning due to anthropogenic warming. With continued greenhouse gas emissions, similar extremes can be expected to become more common, with profound consequences for ecosystems, economies, and societies. While the warming event peaked during summer 2023, anomalously high SST anomalies persisted until the end of 2024, remaining significant even during winter when mixed layers typically deepen. Now in 2025, SSTs remain warm but below the levels experienced during 2023-2024. Several scientific questions remain open, including explaining the persistence of such an extreme heating event out to 24 months.

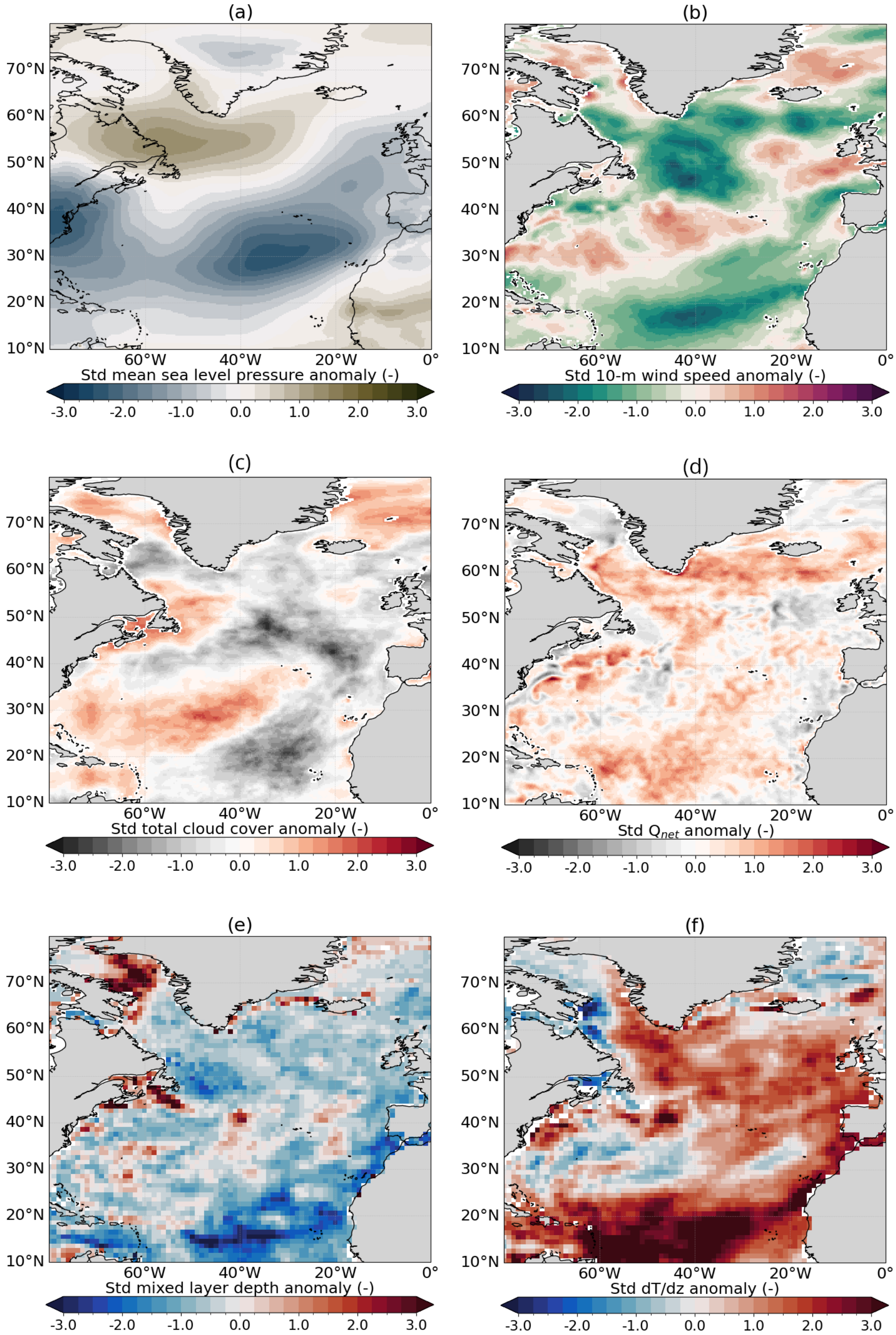


**Figure 2.** Surface ocean-atmosphere conditions in June-July 2023. June-July standardised anomalies from ERA5 in 2023 compared to the 1991–2020 climatological period for (a) mean sea level pressure, (b) 10-m wind speed, (c) total cloud cover, (d) net total surface heat flux, (e) mixed layer depth and (f) vertical temperature gradient.

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# Removing ENSO's influence from global SST variability, with insights into the record-setting marine heatwaves of 2023-2024


**Jacob L. Gunnarson[1*], Yuxin Wang[2,3,4], Alessandro Gagliardi[5], Darren L.C.Y. Li Shing Hiung[3,4], Naoya Takahashi[6,7], Joel Wong[8], Dillon J. Amaya[9], Clara Deser[10]**

[1] Department of Oceanography, University of Hawaiʻi at Mānoa, Honolulu, Hawaiʻi
[2] Cooperative Institute for Marine and Atmospheric Research, University of Hawaiʻi at Mānoa, Honolulu, Hawaiʻi
[3] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia
[4] Australian Research Council Centre of Excellence for Climate Extremes, University of Tasmania, Hobart, Australia
[5] Paleoclimate Dynamics Group, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
[6] Department of Science, Niigata University, Niigata, Japan
[7] International Pacific Research Center, University of Hawaiʻi at Mānoa, Honolulu, Hawaiʻi
[8] Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, Zürich, Switzerland
[9] Physical Sciences Laboratory, Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, Colorado
[10] National Center for Atmospheric Research, Boulder, Colorado
**Correspondence: jlgunnar@hawaii.edu*


## 1. Introduction

The El Niño-Southern Oscillation (ENSO) is the leading mode of global climate variability, and through its atmospheric teleconnections, is an important driver of sea surface temperature (SST) variability far beyond the tropical Pacific. Consequently, ENSO is one of the most important drivers of marine heatwaves (MHWs) (Oliver et al. 2018) – periods of extreme ocean temperatures which can have severe ecological and socioeconomic consequences (Smith et al. 2025).

In July 2023, we were in Trieste, Italy attending the ICTP/CLIVAR Summer School on Marine Heatwaves. There, we began working on a project to quantify ENSO's influence on MHWs. The topic was timely: the warm waters of the Adriatic Sea in which we swam after the days' activities concluded were a symptom of a marine heatwave. Concurrently, during that summer an El Niño event was developing in the tropical Pacific. By the beginning of 2024, ocean temperatures reached record-breaking highs, leading to wide-spread MHWs and coral bleaching on a global scale.

To quantify the impact of ENSO on MHWs, we compared SST anomalies with and without ENSO's influence. To do this, we first determined the best method to remove the influence of ENSO on SST anomalies. Various methods had been used in previous studies to remove ENSO's influence, but there had been no systematic comparison of the efficacy of these methods. Once we determined the method that best removed ENSO's influence, we applied that method to the historical SST anomalies to determine the extent to which the 2023-2024 El Niño was responsible for the concurrent MHWs.

The following is a brief summary of our work, which was recently published in the *Bulletin of the American Meteorological Society* (Gunnarson et al. 2025).

## 2. What is the best way to remove ENSO's influence?

Several methods have been used in previous literature to remove the influence of ENSO from SST anomalies: linear regression on an ENSO index (e.g., Robock and Mao, 1995), eigenmode/empirical orthogonal function (EOF) analysis (e.g., Huang et al. 2024), using a stochastic climate model which includes explicit forcing by ENSO (Gunnarson et al. 2024), and using a Linear Inverse Model to filter ENSO's influence and dynamical evolution (Solomon and Newman, 2012).

To compare the efficacy of these methods we used the Community Earth System Model version 2 (CESM2) Tropical Pacific Pacemaker simulations. Each of the ten ensemble members of this pacemaker experiment has identical ENSO evolution (the tropical Pacific was nudged towards observed SST anomalies from ERSSTv5) but is freely evolving outside the tropical Pacific. Thus, the ensemble mean of the pacemaker members yields only the signal due to ENSO, allowing us to extract the "ENSO-free" SST anomalies to compare with the results from the four methods.

We used two metrics to determine the efficacy of each method. The first was the area-weighted global mean absolute value of the correlation between SST anomalies and the Niño3.4 index averaged over lags of 0, 3, 6, 9, and 12 months (SST lagging Niño3.4, computed between 60°S and 60°N and excluding the pacemaker nudging region in the tropical Pacific). A method that perfectly removed ENSO's influence would result in zero correlation between SST anomalies and the Niño3.4 index at all lags.

However, a second metric is needed because, to give an extreme example, setting SST anomalies to zero everywhere would also yield zero correlation with the Niño3.4 index at all lags. All internal variability unrelated to ENSO would be discarded in this case, which is clearly not desirable. Thus, our second metric compared the variance of the SST anomalies with ENSO's influence removed found using the four methods above and the "ENSO-free" SST anomalies found by subtracting the pacemaker mean from the original SST anomalies. A method that perfectly removed ENSO's influence while also retaining all internal variability unrelated to ENSO would have the same SST variance as the "ENSO-free" SST anomalies from the pacemaker (see the appendix of Gunnarson et al. 2025 for further information).

Considering both metrics, we found that using a stochastic climate model with ENSO forcing was the best way to remove the influence of ENSO. That method, which we termed the "Tendency Regression" method, models the SST anomaly tendency as

$$\frac{dT'(t)}{dt} = \lambda T'(t) + \beta N(t) + \xi(t), \qquad 1$$

where $T'(t)$ is the SST anomaly at each grid point, $\lambda$ is a feedback (damping) coefficient, $\beta$ is an ENSO teleconnection coefficient, $N(t)$ is the Niño3.4 index, and $\xi(t)$ is stochastic (white noise) forcing. Note that $\lambda$ and $\beta$ are seasonally modulated and obtained via multiple linear regression at each grid point, with $\xi(t)$ being the fit residual. The equation is then integrated forward in time without the ENSO teleconnection term $[\beta N t]$ to create an SST anomaly time series free of ENSO's influence.

The Linear Inverse Model method worked almost as well as the Tendency Regression method and yielded very similar results, although it was more complex to implement. The regression and EOF removal methods may be suitable for some applications due to their simplicity but did not perform as well.

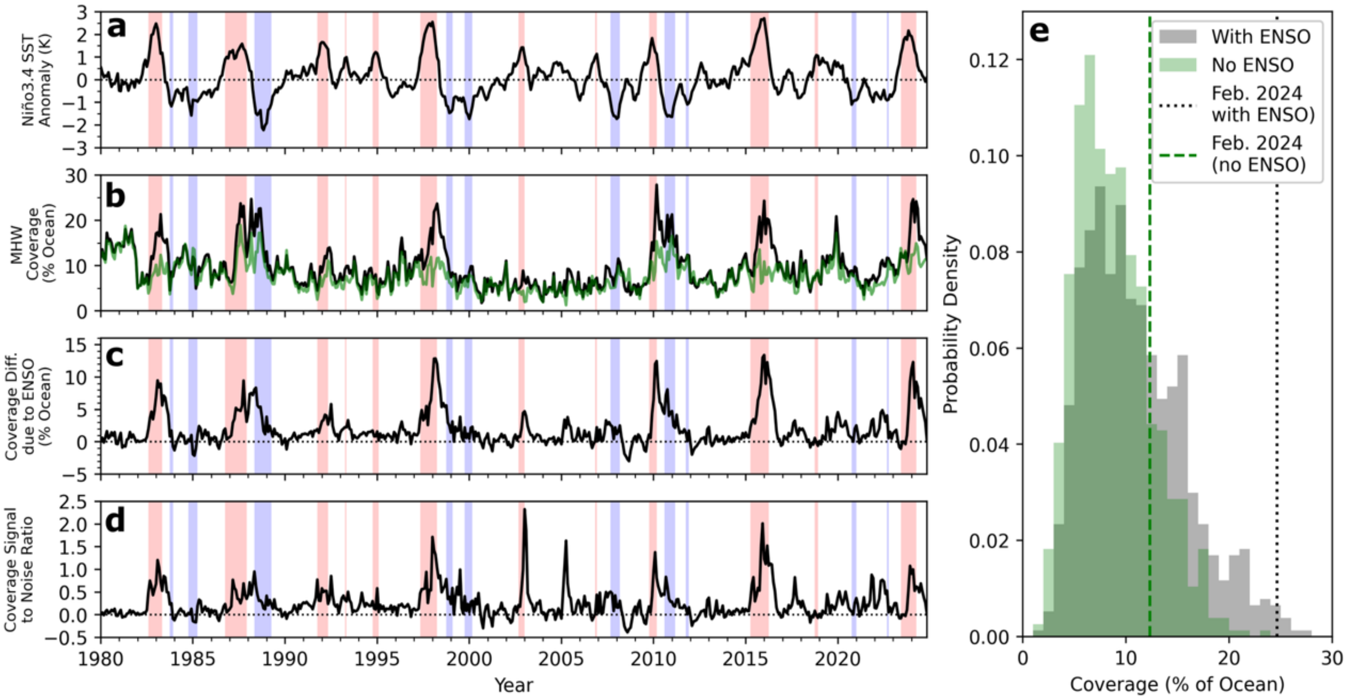


**Figure 1.** ENSO's influence on the spatial coverage of MHWs based on the HadISST dataset. (a) Niño3.4 index. El Niño events are shaded red and La Niña events are shaded blue. (b) Areal percentage of the global ocean (60°S-60°N, excluding the equatorial Pacific: 20°S-15°N, 160°E-70°W) with MHW conditions before ($A_{obs}$; black curve) and after removing ENSO using the Tendency Regression method ($A_{TR}$; green curve). (c) $A_{obs}$ - $A_{TR}$. (d) The ENSO "signal-to-noise" ratio (SNR). (e) Probability density function of $A_{obs}$ (grey) and $A_{TR}$ (green). The February 2024 MHW $A_{obs}$ and $A_{TR}$ values are indicated by the dotted gray and dashed green lines, respectively.

## 3. ENSO's impact on marine heatwaves

After we determined that the Tendency Regression method was the best way to remove the influence of ENSO from SST anomalies, we applied it to the HadISST observational dataset of monthly-mean SST at 1° spatial resolution from January 1960 to November 2024 (Rayner et al. 2003). Monthly anomalies were calculated by removing the climatology for each month separately and then removing the background trend by subtracting the least damped eigenmode using a LIM analysis (see Xu et al. 2022). MHWs were defined as months which exceeded the 90th-percentile SST anomaly for a given calendar month and grid point.

The MHWs of 2023-2024 covered a considerable fraction of the world ocean, thus we used the Tendency Regression method to determine what fraction of that area was directly attributable to the concurrent El Niño event. We define Aobs and ATR as the areal percentage of the global ocean (60°S-60°N, excluding the tropical Pacific) with MHW conditions before and after removing ENSO (using the Tendency Regression method), respectively. We also define a "signal-to-noise ratio" as

$$SNR = \frac{A_{obs} - A_{TR}}{A_{TR}}. \quad 2$$

The SNR represents the contribution from ENSO to the global MHW area relative to the contribution from unrelated internal variability.

During El Niño events, $A_{obs}$ spikes, with peak values between 21% - 27% (24.6% in February 2024; Fig. 1b, black curve). These spikes are greatly reduced or non-existent for $A_{TR}$ (Fig. 1b, green curve), as confirmed by the difference $A_{obs}$ - $A_{TR}$ (Fig. 1c). The maximum MHW area coverage typically lags the peak of an El Niño event by several months, likely due to the effect of the ocean integrating the atmospheric forcing from the ENSO teleconnection.

The SNR also peaks during El Niño, although it reveals that some spikes in global MHW coverage appear to be due to a confluence of the effects of ENSO and random internal variability (Fig. 1d). For example, the 1987-1988 El Niño had maximum SNRs of 1.0, indicating that the MHW coverage due directly to the El Niño was comparable in magnitude to that caused by other forms of internal variability. In contrast, the 2015-2016 El Niño had the highest observed SNR of 2.2, thus about 2/3[rd] of the total MHW area was caused directly by the El Niño.

The 2023-2024 El Niño had a maximum SNR of 1.1 (in December 2023), with an SNR of 1.0 at the peak of the MHW coverage in February 2024 and an average of 0.7 between January and May 2024. This suggests

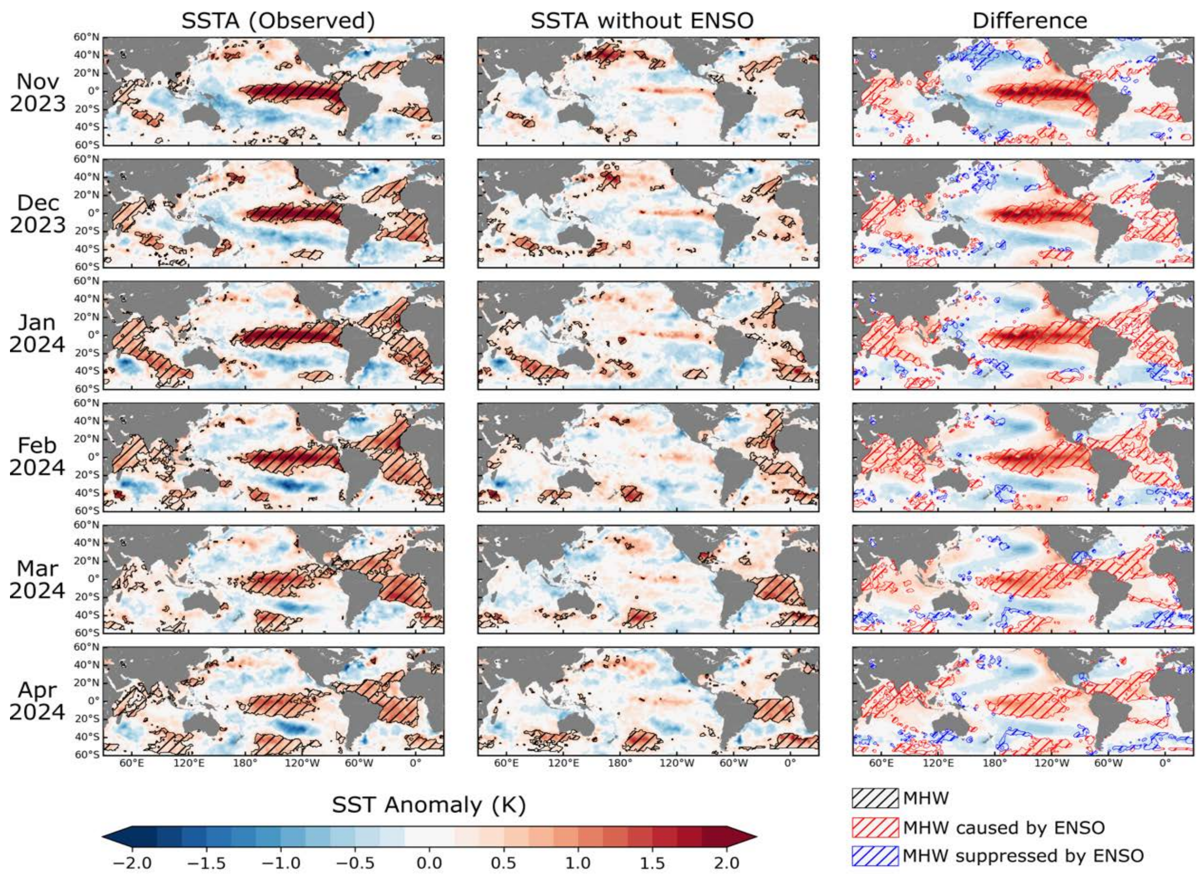


**Figure 2.** Evolution of the 2023-2024 El Niño and associated MHWs. (Left column) observed SSTAs from HadISST with MHWs outlined and hatched in black. (Middle column) SSTAs and MHWs without the influence of ENSO calculated using the Tendency Regression method. (Right column) Difference between observed and ENSO-removed SSTAs and MHW. Areas where ENSO's influence caused MHWs are hatched in red; areas where ENSO suppressed MHWs are hatched in blue.

that internal variability unrelated to ENSO was roughly as important in generating the extensive global MHW coverage during that event as the El Niño was. Nevertheless, a histogram of MHW spatial coverage (Fig. 1e) shows that the maximum spatial coverage of MHWs in 2023-2024 was beyond that caused only by internal variability unrelated to ENSO. Thus, the widespread nature of MHWs in February 2024 could not have occurred without El Niño's influence.

### 4. 2023-2024 marine heatwaves without El Niño

Figure 2 shows the spatial structure and evolution of the 2023-2024 El Niño and its effect on global MHWs. The influence of ENSO can be gleaned by the difference between the observed SSTAs and those computed via our Tendency Regression method. In the Indian Ocean, the El Niño warmed the western half of the basin, leading to a positive-phase Indian Ocean Dipole (IOD) event in the fall and winter of 2023, which then transitioned to basin-wide warming in early 2024. This sequence and its relationship with ENSO is consistent with previous studies (e.g., Stuecker et al. 2017). With ENSO's influence removed, the IOD pattern was considerably diminished, and MHWs remained only in the southern Indian Ocean.

The El Niño's role in the North Pacific was to suppress MHWs in the central part of the basin (in November and December 2023), and enhance them along the west coast of North America, through the well-known "atmospheric bridge" which links ENSO to the North Pacific via atmospheric teleconnections (Alexander et al. 2002; Lau and Nath, 1996). MHWs were enhanced in the South Pacific, likely a result of the Pacific-South American modes of atmospheric variability, which carry ENSO's influence to the South Pacific (Mo and Higgins, 1998).

In the Atlantic Ocean, a considerable portion of the MHW coverage during 2023-2024 appears to have originated from internal variability unrelated to ENSO, as evidenced by the sizeable MHW area that remains after the ENSO's influence is removed, particularly in the South Atlantic after February 2024 (Fig. 2, middle column). Nevertheless, the El Niño contributed to MHWs in the tropical Atlantic as well as MHWs in the subtropical North and South Atlantic (Fig. 2, right column). Warming in the tropical and subtropical North Atlantic has been linked to El Niño (Alexander and Scott, 2002) as has warming in the subtropical South Atlantic (Rodrigues et al. 2015). Thus 2023-2024 MHWs in the Atlantic, which covered a large part of the basin, originated from a confluence of ENSO and internal climate variability unrelated to ENSO.

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# Assessment of Deterministic and Probabilistic Seasonal Prediction Skill of the Indian Summer Monsoon and its Teleconnections

**Maheswar Pradhan[1*], Suryachandra A. Rao[1], Ankur Srivastava[1], Satyaban Bishoyi Ratna[2],**

[1] Monsoon Mission, Indian Institute of Tropical Meteorology, Pune, India
[2] Climate Research and Services, India Meteorological Department, Pune, India.
**Correspondence: maheswar@tropmet.res.in*

## 1. Rationale

Accurate prediction of the Indian Summer Monsoon Rainfall (ISMR) is critical for agricultural planning, water resource management, and disaster mitigation across the Indian subcontinent. However, the complex interactions between the monsoon system and large-scale climate drivers such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) pose significant challenges to seasonal forecasting. Studies like Pillai et al.(2018) have compared the deterministic forecast skill of ISMR, ENSO, etc. On the other hand, studies like Becker and van den Dool (2016) have evaluated North American Multi-Model Ensemble (NMME) models probabilistic skill (Brier skill Score, reliability diagrams) for 2-m surface temperature, precipitation, and sea surface temperature (SST) over larger domains such as the tropics, the Northern Hemisphere, and the Pacific. The performance of NMME models probability skill for Indian monsoon rainfall remains unaddressed. Hence, the present study aims to evaluate the deterministic and probabilistic seasonal prediction skills of NMME and the Monsoon Mission Climate Forecast System Version 2 (MM-CFSv2) models in simulating ISMR. Specifically, the study investigates how prediction skill varies with forecast lead time and explores the influence of ENSO prediction skill on ISMR forecasts through associated large-scale teleconnections. By identifying model strengths and limitations, this work seeks to advance understanding of monsoon predictability and enhance the reliability of operational seasonal forecasting systems for the Indian region.

## 2. Methodology

The following deterministic and probabilistic skill scores are used to evaluate model performance for the simulation of ISMR and ENSO.

a. Anomaly Correlation Coefficient (ACC)
b. Ranked Probability Skill Score (RPSS)
c. Relative Operating Characteristic Score(ROCS)

The following observational datasets are used for model validation, and their details can be found in the references mentioned.

a. India Meteorological Department (IMD) Rainfall (Rajeevan et al. 2006)
b. Global Precipitation Climatology Project (GPCP) Rainfall version 2.3 (Adler et al. 2018)
c. Indian Institute of Tropical Meteorology (IITM) Rainfall (Sontakke et al. 2008)
d. Optimum Interpolation Sea Surface Temperature (OISST) version 2.1 (Huang et al. 2021)

The present study involves an analysis of the following coupled models, and their details can be found in the references mentioned below:

a. Monsoon Mission Climate Forecast System Version 2 (MM-CFSv2; Rao et al. 2019)
b. NMME (Kirtman et al. 2014)
   i. CanCM4i
   ii. CanSIPSv2
   iii. COLA_RSMAS-CCM3
   iv. COLA-RSMAS-CCM4
   v. GEM-NEMP
   vi. GFDL-CM2p1-aer04
   vii. GFDL-CM2p5-FLOR-A06
   viii. GFDL-CM2p5-FLOR-B01
   ix. NASA-GEOSS2S
   x. NASA-GMAO-062012

## 3. Results

### 3.1. Deterministic Skill of ISMR

The anomaly correlation coefficient (ACC) represents the deterministic skill of ISMR for various models and is computed after detrending the respective rainfall anomaly time series. ACC for all the models is shown in Figure 1 (a-c), where positive ACCs are coloured. The figure shows that most models exhibit higher correlations with GPCP than with IITM and IMD datasets. The correlations with the IMD dataset are notably different from those with the other two datasets. Such differences in values of ACC with different observational datasets arise because of different spatial resolutions of the datasets, errors in re-gridding, and errors due to the incorporation or omission of grid cells in the demarcation of the landmass, apart from the intrinsic biases of the datasets. Most models (e.g., Canadian models, GEM-

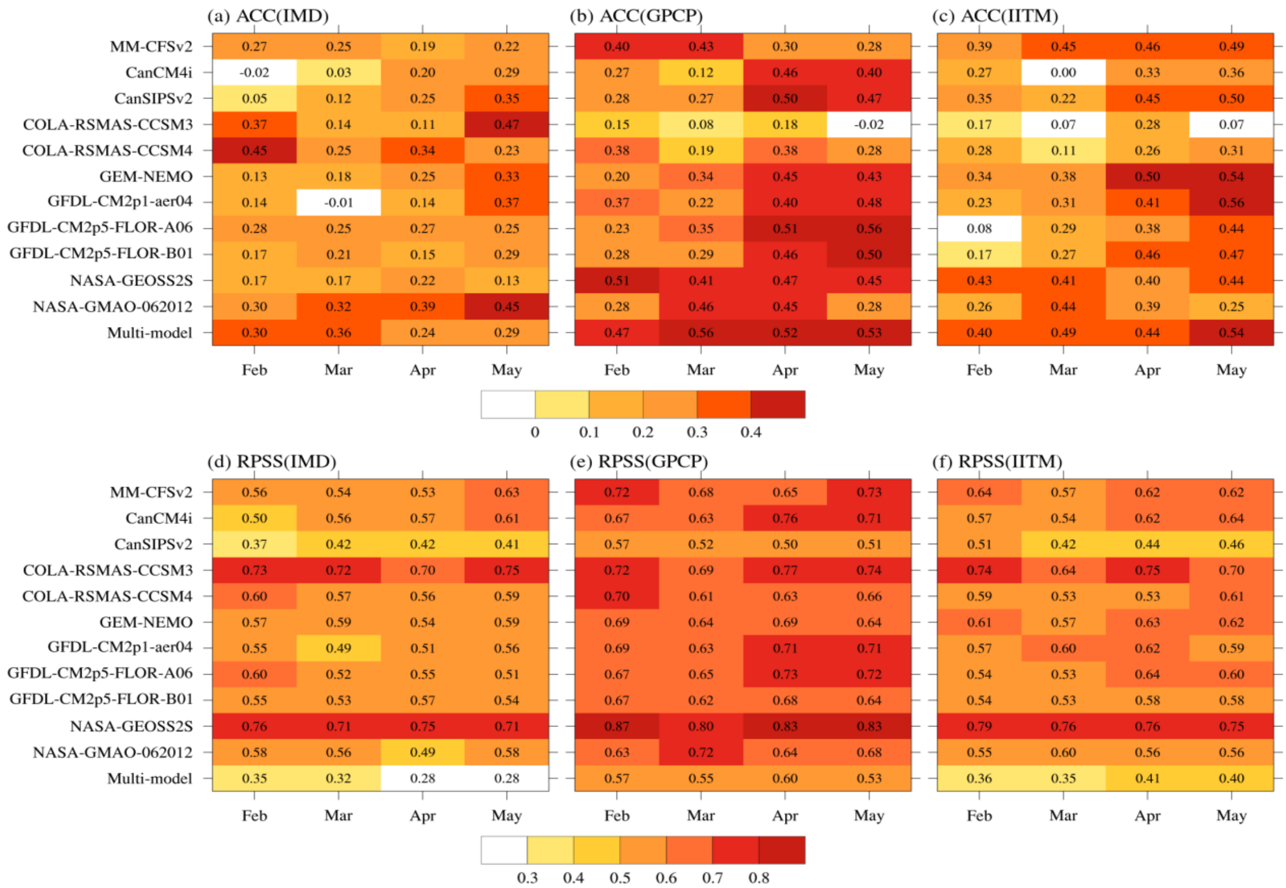


**Figure 1.** ACC and RPSS for ISMR using (a, d) IMD, (b, e) GPCP, and (c,f) IITM observational datasets for the period 1988-2016.

NEMO, and GFDL) show an increase in prediction skill as the lead time decreases (i.e., going from February to May initial conditions) except MM-CFSv2. In MM-CFSv2, the prediction skill of ISMR decreases as the lead time decreases, except when the skill is computed with respect to the IITM rainfall time series. The reason for such behavior is due to the inefficiency of the model to handle the initial shock from the May initial condition (IC), resulting in biases in the sea surface temperature (SST) and circulation in the Arabian Sea, yielding a drop in the skill score (Shukla et al. 2018). On the other hand, a few models (COLA and NASA models) do not show any increasing or decreasing pattern in prediction skill with lead time.

### 3.2. Probabilistic Skill of ISMR

The Ranked Probability Skill Score (RPSS) for different models (Fig. 1d-f) also shows higher skill with GPCP than the IITM and IMD datasets. From the figure, it can be noted that models with better RPSS may not coincide with the models with better ACC. In addition, there is no clear pattern of decreasing or increasing RPSS for models as the lead time decreases. Most models have their highest RPSS skill scores (mostly greater than 0.5) with April or May initialized hindcasts.

Relative Operating Characteristics Score (ROCS) represents the skill of models under categorical forecasts, such as the below-normal, near-normal, and above-normal monsoon conditions. Figure 2 shows the ROCS scores for various models for the above-mentioned three forecast categories. Similar to RPSS and ACC, ROCS scores are also higher with GPCP than with the IMD and IITM datasets for all three categories. In terms of models, predictions of seasonal mean rainfall during extreme (above and below normal) monsoon years are overall better than normal monsoon years, considering their higher ROCS for the above and below normal categories. With April's initial conditions, the ROC scores for extreme monsoon years are above the climatological skill scores. With May's initial condition, the ROC scores are better for only above-normal years. For extreme monsoon years, about 70% of the models have higher skills of 0.7 or more. The above-normal category displays an even better skill score than the below-normal category, with fewer variations in the skill scores.

### 3.3. Skill of Niño3.4

ENSO is the dominant forcing in the tropics at the seasonal timescale and the most significant contributor to the inter-annual variability of ISMR, and its prediction skill significantly impacts ISMR's prediction skill. The deterministic skill, i.e., ACC for various models (Fig. 3a), shows that models overall have better skills with April and May initial conditions. The forecasts initialised

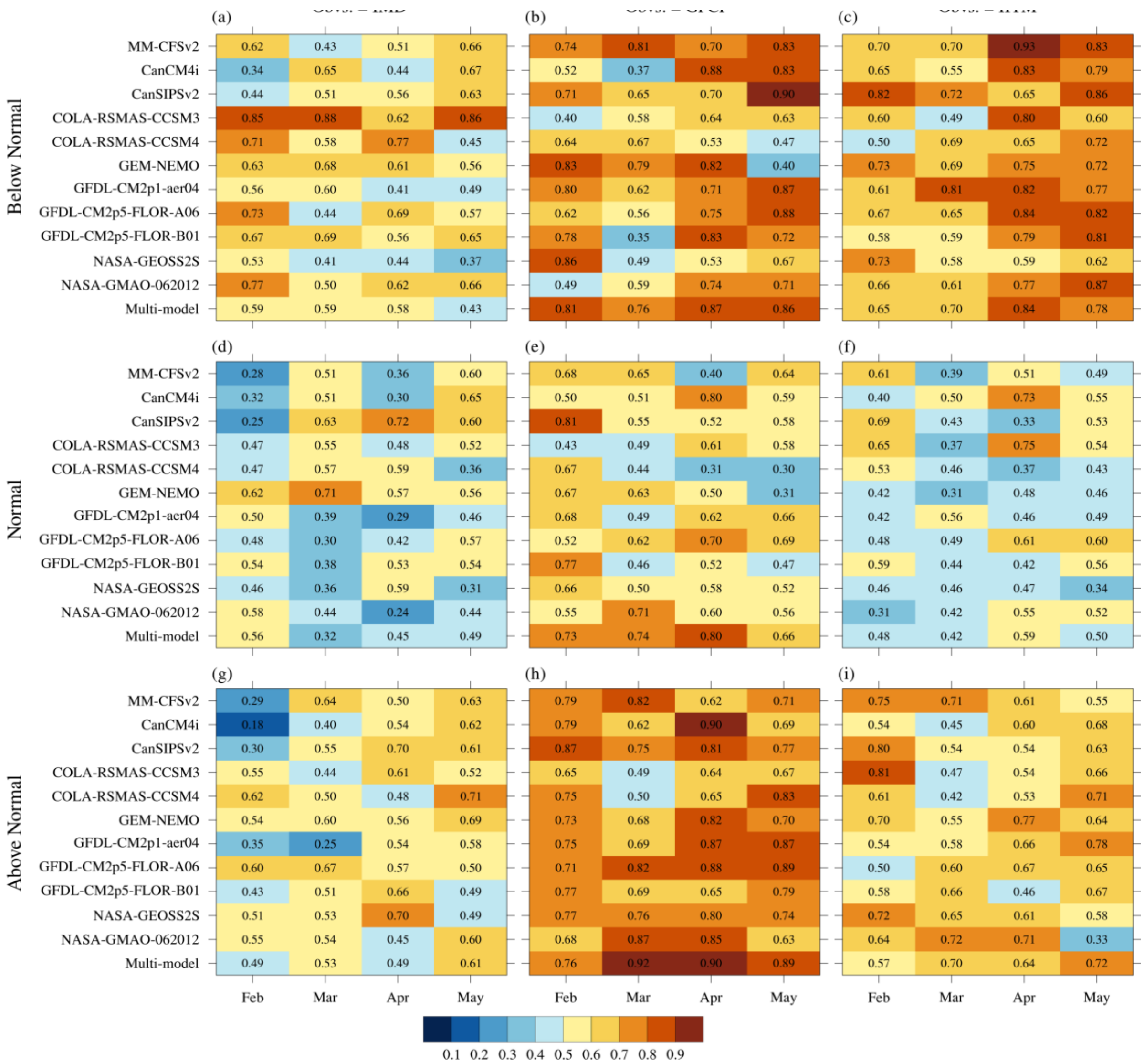


**Figure 2.** ROC Score for ISMR for (a,b,c) below normal, (d,e,f) normal and (g,h,i) above normal rainfall category using (a,d,e) IMD, (b,e,h) GPCP and (c,f,i) IITM as observational datasets during the period 1988-2016.

during March to April are often associated with the spring predictability issues, a period during which the prediction skill of ENSO, IOD or ISMR significantly decreases compared to forecasts initialised in other months (Barnston et al. 2019; Ehsan et al. 2024). The Niño3.4 prediction skill increases as the lead time decreases in 80% of the models considered here. Except for models like MM-CFSv2, GFDL-CM2p1-aer04, GFDL-CM2p5-FLOR-B01, and NASA models, all the other models show linear improvement in the ACC when comparing hindcasts with Feb, Mar, Apr, and May IC. The RPSS of the Niño3.4 SST with the NOAA OISST shows that all the models except CanSIPSv2 display skill scores greater than 0.5 (Fig. 3b). A few models, for example, CanCM4i, COLA-RSMAS models GFDL-CM2p1-aer04, NASA-GEOSS2S, and NASA models, stand out among the rest with scores above 0.7. The ROC scores of the Niño3.4 SST show that the extremes are well-captured compared to the neutral conditions (Fig. 3c, d, and e). 70 to 80% of the models considered here have scores around 0.8, indicating higher skills of the model. The skill of ENSO forecasts in models is better than their respective ISMR skill. Additionally, the performance of categorical forecasts for ENSO is better than ISMR, as evident from Figures 2 and 3.

## 4. Summary

The deterministic and probabilistic skills for ISMR prediction in the NMME and MM-CFSv2 models are found to vary with the initial conditions and the reference observed dataset under consideration. Most of the models have better probabilistic scores with April and May initial conditions. Also, the models have better skill for above and below normal rainfall years than for normal years. Since ENSO is the dominant driver of monsoon variability through large-scale ocean–atmosphere teleconnections, improved prediction skills of ENSO, the IOD, and their associated teleconnection patterns enhance the ability of climate models to realistically simulate monsoon variability, including the occurrence of above- and below-normal monsoon seasons.

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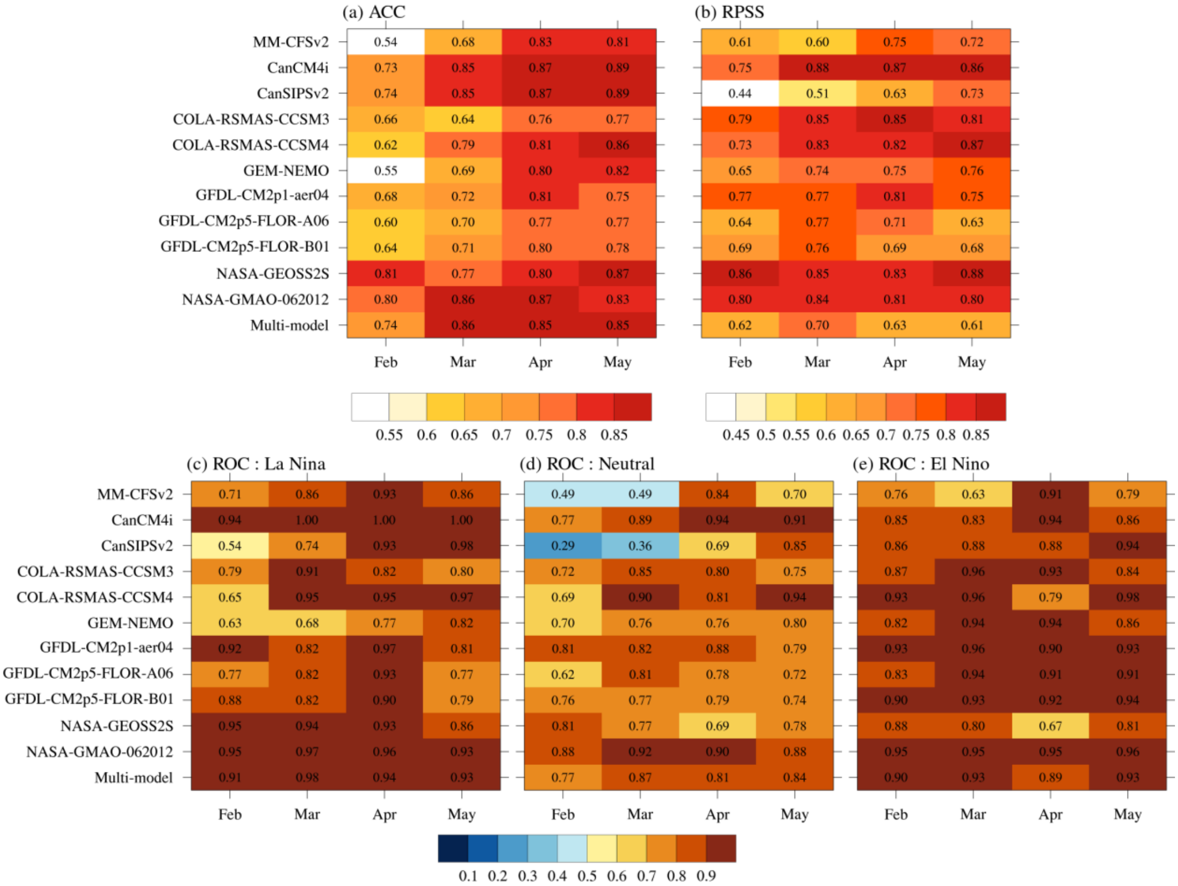


**Figure 3.** (a) ACC, (b) RPSS and (c,d,e) ROC for Nino3.4 SST using NOAA OISST as observational datasets for the period 1988-2016. ROC Score for (c) La Nina, (d) Neutral and (e) El Niño conditions are shown separately.

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# ENSO phase transitions in Observation and Monsoon Mission Coupled Forecasting System

**Satyaban B. Ratna[1*], Jasmine Takle[1,2], Madhuri Musale[1], Tanu Sharma[1,2], C.T. Sabeerali[1], O.P. Sreejith[1], Arvind Pagire[1,2], Prasanth A. Pillai[3]**

[1] Climate Research and Services, India Meteorological Department, Pune, India
[2] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India
[3] Indian Institute of Tropical Meteorology, Pune, India
*Correspondence: satyaban.ratna@imd.gov.in*

## 1. Introduction

Many previous studies have highlighted the influence of the El Niño-Southern Oscillation (ENSO) on various global and regional climate systems (Rajeevan and Pai, 2007). That is why the skill of most coupled climate models depends on how well they predict the ENSO phases in advance (Pillai et al. 2017). The Monsoon Mission Coupled Forecasting System (MMCFS), a project initiated by the Ministry of Earth Sciences (MoES) of the Government of India (Rao et al. 2019), has been used by the India Meteorological Department (IMD) for operational forecasting since 2017. The ENSO forecast is generated for the next nine months (seven running 3-month seasons), and accordingly, an ENSO forecast bulletin is issued every month (Pai and Nair, 2022; Ratna et al. 2025).

ENSO phases significantly influence the Indian summer monsoon rainfall (ISMR) as reflected by a significant correlation between the ISMR and the simultaneous as well as preceding ENSO conditions (e.g., Ratna et al. 2024; Sharma et al. 2024). Apart from the ENSO phases, predicting the transition between ENSO phases is another crucial aspect, as the timing of these transitions has significant implications for various climate-sensitive sectors, including agriculture (Kakoti et al. 2023), water resource management, and disaster preparedness (Wang et al. 2024). The onset of El Niño or La Niña can lead to significant shifts in climate patterns, including changes in rainfall and temperature over India. This ENSO-ISMR association motivates us to investigate how well the MMCFS model predicts the ENSO phases and their transition (Ratna et al. 2025). Here, we further explored the ENSO phase transition aspect, which is also profoundly useful in mitigating social and economic consequences.

## 2. Data and Methods

The sea surface temperature (SST) data are sourced from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Monthly Sea Surface Temperature version 5 (ERSSTv5) at a 2° x 2° spatial resolution (Huang et al. 2017). The Oceanic Niño Index (ONI), which represents the 3-month running mean SST anomaly averaged over the Niño 3.4 region (5°N-5°S and 120°W-170°W), is sourced from NOAA. The analysis is conducted for the 30-year period, 1991–2020.

The ocean component of MMCFS consists of the Geophysical Fluid Dynamics Laboratory (GFDL) Flexible Modeling System (FMS) and the Modular Ocean Model version 4p0d (MOM4), with a horizontal resolution of 0.25° near the equator, 0.5° in the subtropics, and 40 vertical levels (Griffies et al. 2004). All the analyses using MMCFS are based on an ensemble mean of 10 members. The initial conditions (ICs) in MMCFS for the target season, February to April (FMA), are considered starting from January (lead 1), December (lead 2), November (lead 3), and so on, up to July (lead 7). Similar lead definitions are applied for the other target seasons. We compared the SST anomalies of the model with observations for four types of ENSO phase transitions: (i) La Niña to Neutral, (ii) El Niño to Neutral, (iii) Neutral to La Niña, and (iv) Neutral to El Niño. A La Niña (El Niño) to Neutral transition is defined as when ONI becomes greater (lesser) than −0.5 °C (0.5 °C) and persists for the next five consecutive running seasons (e.g., MJJ, JJA, JAS, ASO, SON). Similarly, a Neutral to La Niña (El Niño) transition season is defined when ONI becomes lesser (greater) than −0.5 °C (0.5 °C) and persists for the next five consecutive running seasons. All model outputs are regridded to match the spatial resolution of the observations. To evaluate the performance of MMCFS in simulating ENSO phase transitions, here we analyzed whether MMCFS accurately predicts the timing of various ENSO phase transitions.

## 3. Results

To compare MMCFS output with the observed Niño 3.4 index, the Index of Agreement (IOA), shown in Fig. 5 in Ratna et al. (2025); and other skill metrics were analyzed. Their study indicated that IOA were higher (up to lead-5 and lead-6) during the autumn and winter (OND to JFM) seasons compared

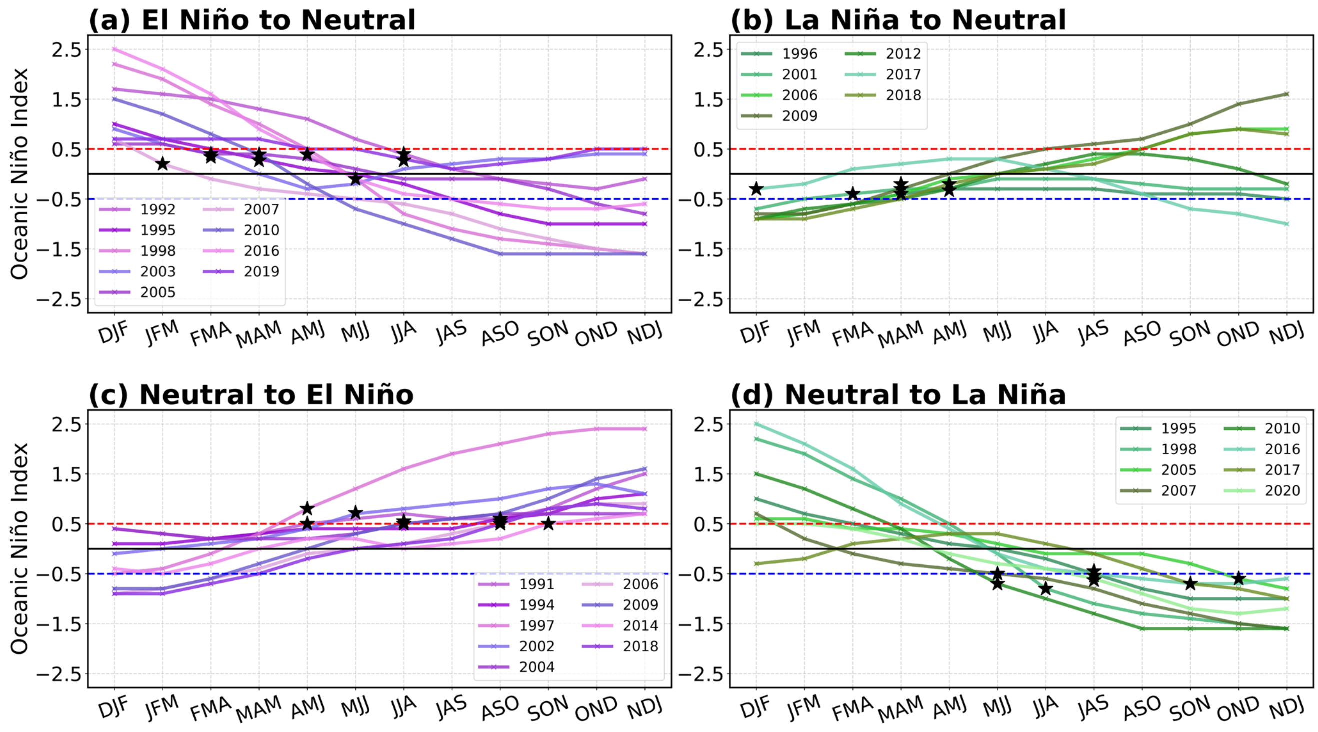


**Figure 1.** Observed evolution of the Oceanic Niño Index (ONI) for ENSO transitions from (a) El Niño to Neutral, (b) La Niña to Neutral, (c) Neutral to El Niño, and (d) Neutral to La Niña, during the period 1991–2020. Black stars represent the respective transition seasons (adapted from Ratna et al. 2025).

to other seasons. This could be due to the ocean's natural tendency to maintain a memory (persistence) and the model's capability to simulate the ocean-atmosphere interaction, which further improves the ENSO prediction. For the boreal spring season, the IOA is reasonably high up to lead-3 and gradually drops afterwards, potentially due to the spring predictability barrier.

We further explored the MMCFS model's ability to capture transitions between different ENSO phases and analyzed the model forecast (See Section 2 for methods). According to Choi et al. (2015), the transition from El Niño to Neutral phase (or La Niña) typically begins within a year, while the transition from La Niña to Neutral phase (or El Niño) occurs less frequently, often taking two or more years. In our study period from 1991 to 2020, there were seven transitions from La Niña to Neutral, nine from El Niño to Neutral, eight from Neutral to La Niña, and nine from Neutral to El Niño. Fig. 1 shows the season-wise evolution of these four types of observed ENSO transitions. The transitions from El Niño to Neutral phase (Fig. 1a) took place during the boreal spring and summer seasons, whereas La Niña to Neutral phase transitions (Fig. 1b) predominantly during the boreal spring season. Transition from Neutral to El Niño (Fig. 1c) as well as Neutral to La Niña (Fig. 1d) occurred during the boreal summer and fall seasons. During this period, spanning six years (1995, 1998, 2005, 2007, 2010, and 2016), there were transitions from El Niño to Neutral to La Niña within a short time of a few months. These transitions, especially during the boreal summer season, significantly enhance rainfall over the south peninsula and west-central India while reducing rainfall over the Indo-Gangetic plains of India (Sharma et al. 2024). So the model guidance becomes crucial in predicting such ENSO phase transitions.

We analyzed the MMCFS model's ability to capture the timing of observed transitions of different ENSO phases using lead-1 initial conditions (Fig. 2). Out of nine El Niño to Neutral transitions, MMCFS captured four transitions (1992, 1995, 2003, 2016) in the same season as found in observation, three transitions (1998, 2005, 2019) occurred one season ahead, while two transitions (2007, 2010) occurred with a delay of one season (Fig. 2a). Out of seven La Niña to Neutral transitions, MMCFS completely missed two transitions (2001, 2017), two transitions (2006, 2009) occurred one season ahead, two transitions (1996, 2012) occurred two seasons ahead, while the transition in 2018 occurred with a delay of two seasons (Fig. 2b). Out of nine Neutral to El Niño transitions (Fig. 2c), MMCFS completely missed the transition in 2018 but predicted two transitions (2006, 2009) in the same season as found in observation. The transition in 2014 occurred one season ahead, the transition in 2002 occurred two seasons ahead, while the transition in 1997 had a one-season delay in MMCFS. Two transitions (1994, 2004) showed a two-season

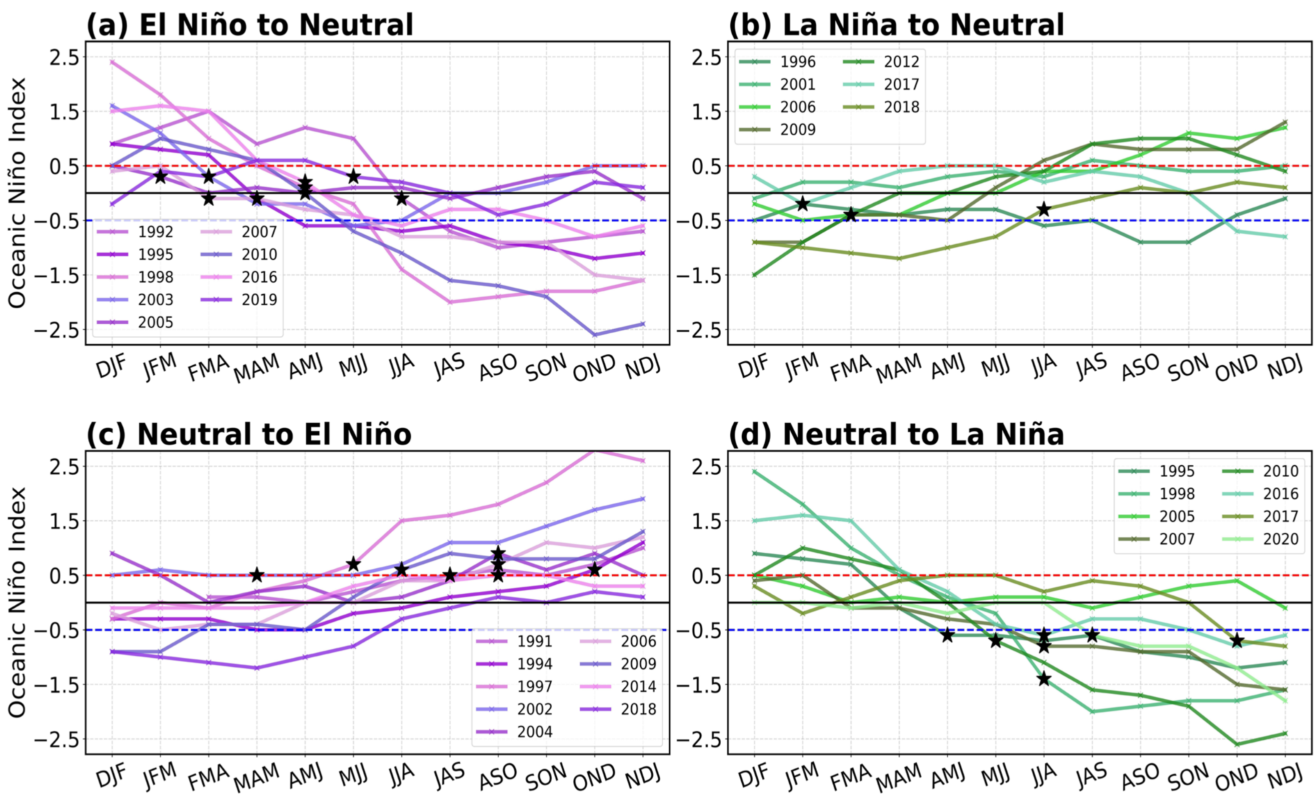


**Figure 2.** Same as Figure 1 but with the MMCFS Lead-1 forecast.

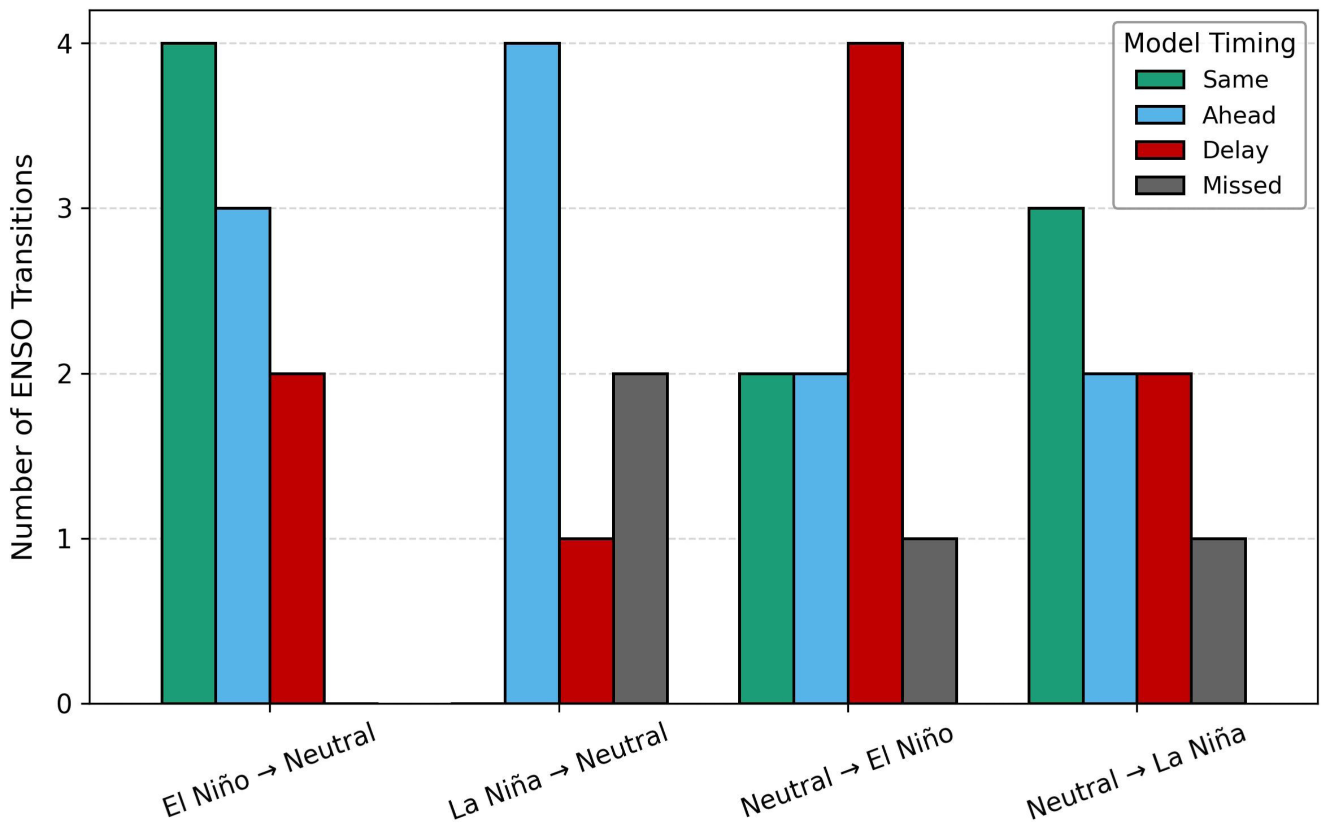


**Figure 3.** MMCFS model performance in predicting the timing of four types of ENSO phase transitions (as shown in Figure 1) using lead-1 forecast during 1991–2020. The bars show the model either reproducing the transitions in the same season (green), ahead (blue), and delayed (red) relative to observations, or missing the observed transitions (grey).

delay, while the transition in 1991 showed a three-season delay in the model. Out of eight Neutral to La Niña transitions (Fig. 2d), MMCFS completely missed the 2005 transition but predicted three transitions (1998, 2010, 2020) in the same season as found in the observation. The transition in 2016 occurred one season ahead, the transition in 1995 occurred three seasons ahead, while two transitions (2007, 2017) occurred with a one-season delay in MMCFS. Overall, the MMCFS demonstrates limited skill in simulating the transition from La Niña to Neutral phase. In contrast, the model exhibits its highest fidelity during El Niño to Neutral transitions, with no missed events. Notably, MMCFS accurately captures four such transitions within the same season as observed, while the remaining cases display only a modest deviation of one season, either as a lead or a lag (Fig. 3).

## 4. Conclusions

This study assessed the predictive capabilities of the MMCFS model for ENSO phase transitions. While MMCFS reasonably captures the broad sequence of ENSO phase transitions, a notable variation was observed in the model's ability to predict the exact timing of transitions among different ENSO phases. The model performs relatively better in predicting the timing of El Niño to Neutral transition, and Neutral to La Niña transitions, but tends to show systematic leads or delays for La Niña to Neutral, and Neutral to El Niño transitions. These biases suggest limitations in simulating the ocean–atmosphere feedbacks governing ENSO evolution, particularly during the decay of the La Niña phase. Potential areas for further enhancement in prediction include examining the model's ability to capture variations in trade wind direction and strength (e.g., Arora et al. 2018), warm water advection, and oceanic Rossby and Kelvin waves – topics that offer promising scope for future research. The insights gained in this study may be useful for stakeholders across various sectors to make informed decisions and develop more effective adaptive strategies to manage the socio-economic impacts of ENSO-related climate variability.

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# Teleconnection Index Online Tool: an updated version

**Anita Drumond[1], Natan C. de Oliveira Nogueira[2*], Michelle S. Reboita[3], and Geovane C. Miguel[2]**

[1] Instituto Tecnológico Vale, Rua Boaventura da Silva, 955, Belém -PA, Brazil
[2] Universidade Federal de Itajubá (UNIFEI), Av. BPS, 1303, Itajubá - MG, Brazil
*Correspondence: reboita@unifei.edu.br

## Abstract

Subseasonal-to-seasonal (S2S) climate forecasting remains a challenge due to the complex nature of climate variability and the large spread in model outputs. Forecasters often infer teleconnection indices within their models and observational products to explain their predictions; in addition, they use the observed indices to validate the simulated ones. Teleconnection indices are not only useful for S2S, but also for research purposes and climate-state monitoring. Because the observed teleconnection indices available from different operational meteorological agencies use different baseline periods and datasets, we present, in this work, an updated version of our teleconnection index online tool that provides indices using the 1991–2020 climatological period and specific products (ERA5 and ERSSTv5). The indices are freely accessible through an online platform designed to support the broader scientific community: https://app-indice.streamlit.app/.

## 1. Introduction

The climate of a region frequently deviates from its average conditions due to the influence of natural climate variability. Events occurring in a specific ocean basin, for instance, can impact weather and climate in distant regions through what is known as teleconnection (Liu and Alexander, 2007). There are various teleconnection patterns occurring simultaneously. To facilitate their monitoring, scientists have developed oceanic and atmospheric indices (e.g., those indicated in Table 1 and in Reboita et al. 2021; Souza and Reboita, 2021). These indices, known as teleconnection indices, play a critical role in subseasonal-to-seasonal (S2S) forecasting. Because sea-surface temperature (SST) anomalies tend to persist from one month to the next due to the ocean's thermal inertia, monthly SST conditions often exhibit positive month-to-month autocorrelation. Using this persistence, quantified through teleconnection indices, alongside dynamical model–forecasted indices can improve S2S forecasts.

To support the scientific community and operational forecasters, Souza and Reboita (2021) developed an online tool that compiles more than 25 climate indices from different operational meteorological agencies and displays them through an interactive visualizations, available at: https://meteorologia.unifei.edu.br/teleconexoes/. Nevertheless, most of these indices were obtained from international meteorological centers, which may, in some cases, rely on different datasets and climatological baselines.

Over time, user feedback raised concerns about inconsistencies related to differing datasets and climatological baselines. These concerns underscored the need to standardize all indices by applying the same data sources and the same climatological reference period. Indeed, in a recent discussion on El Niño-Southern Oscillation (ENSO) indices, Dr. Michelle L'Heureux emphasized how using different climatological periods can significantly affect the characterization of climate phenomena (WMO, 2025).

In this context, the objective of this study is to present an updated version of the teleconnection index online tool, which now calculates the indices using the same datasets and the 1991–2020 reference period, as recommended by the World Meteorological Organization (WMO, 2017).

## 2. Methodology

Climatic indices are computed using atmospheric variables (mean sea level pressure - MSLP -, and geopotential height - HGT - at 1000 and 500 hPa) on a 2.5° grid from the ERA5 reanalysis (Hersbach et al. 2020), provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) on monthly basis. Hourly data (outgoing longwave radiation and zonal winds) are used only for the Madden-Julian Oscillation (MJO) index. Sea surface temperature (SST) is taken from the NOAA Extended Reconstructed Sea Surface Temperature (ERSST) version 5 (Huang et al. 2017), with 2° resolution and monthly frequency.

**Table 1.** Teleconnection indices calculated in Teleconnection Index Online Tool and their methodologies. Note that all the indices are monthly, except MJO (vide text for details).

| Region | Index (Unit) | Methodology | Reference |
| --- | --- | --- | --- |
| Tropical Pacific Ocean | Niño 1.2, 3, 3.4 and 4 (°C) | SST anomalies are computed for each region representative of the different Niños: Niño 1.2: 90°W-80°W and 0°-10°S; Niño 3: 150°W-90°W and 5°N-5°S; Niño 3.4: 120°W-170°W and 5°N-5°S, and Niño 4: 160°E-150°W and 5°N-5°S | https://psl.noaa.gov/data/climateindices/list/ Trenberth (1997) |
| Tropical Pacific Ocean | SOI (dimensionless) | The Southern Oscillation Index (SOI) is calculated using standardized MSLP anomalies from Tahiti and Darwin. The SOI is computed by subtracting the standardized Darwin value from the standardized Tahiti value and dividing by their monthly standard deviation. | https://www.cpc.ncep.noaa.gov/data/indices/Readme.index.shtml#SOICALC Walker (1928) |
| Atlantic Ocean | TSA and TNA (°C) | The Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) indices represent the two components of the Tropical Atlantic Dipole. The TSA index is defined by monthly SST anomalies averaged over the region 0°–20°S, 10°E–30°W, while the TNA index is based on SST anomalies averaged over 5.5°–23.5°N, 15°W–57.5°W. | https://psl.noaa.gov/data/climateindices/list/ Enfield et al. (1999) |
| Atlantic Ocean | SAODI and SASDI (°C) | The South Atlantic Ocean Dipole (SAODI; Nnamchi et al. 2011) and the South Atlantic Subtropical Dipole (SASDI; Morioka et al. 2011) indices capture distinct aspects of South Atlantic Dipole variability (Nnamchi et al. 2017). The SAODI is defined as the difference between domain-averaged SST anomalies over the northeast pole (NEP; 10°E–20°W, 0°–15°S) and the southwest pole (SWP; 10°W–40°W, 25°–40°S). In contrast, the SASDI defines the NEP as 0°–20°W, 15°S–25°S, and the SWP as 10°W–30°W, 30°S–40°S. Originally, the SASDI was defined as the difference between the SWP and the NEP. Here, we inverted this definition to maintain consistency between both indices. | The main authors do not provide the indices in operational mode. These indices were provided in the first version of the Teleconnection Online Tool (https://meteorologia.unifei.edu.br/teleconexoes/). |
| Atlantic Ocean | SAD (dimensionless) | The South Atlantic Dipole (SAD) index is computed from standardized SST anomalies over the South Atlantic Ocean, using the monthly standard deviation for the 1991–2020 period. Following the approaches of Morioka et al. (2011) and Nnamchi et al. (2011), Empirical Orthogonal Function (EOF) analysis is applied separately for each calendar month. The gridded SST data are weighted by the square root of the cosine of latitude to ensure equal-area representation in the covariance matrix. The EOF mode corresponding to the SAD spatial pattern is then selected. Monthly SAD indices are obtained by projecting the SST anomalies onto the selected EOF and normalizing by the standard deviation for 1991–2020. | Nogueira et al. (2025) in preparation |
| Atlantic Ocean | SASAI (hPa) | The South Atlantic Subtropical Anticyclone Index (SASAI) is calculated by computing the difference between the monthly MSLP anomalies averaged in the Brazilian southeastern region (25ºS–15ºS, 50ºW–40ºW) and the southern region (37.5ºS–27.5ºS, 60ºW–50ºW). | https://meteorologia.unifei.edu.br/teleconexoes/ Souza and Reboita (2021) |
| Atlantic Ocean | SSTRG2 (°C) | Index defined by the monthly SST anomalies averaged over the cyclogenetic region located between Uruguay and the extreme south of Brazil (RG2): 40ºS-30ºS and 57º-47ºW | |

| | | | |
|---|---|---|---|
| Indian Ocean | IOSD (°C) | The Indian Ocean Subtropical Dipole (IOSD) index is defined as the difference between monthly SST anomalies averaged in the western (55°E–65°E, 27°S–37°S) and eastern (90°E–100°E, 18°S–28°S) centers of the dipole. | www.jamstec.go.jp/apl/j/members/behera/iosd.html Behera and Yamagata (2001) |
| | DMI (°C) | The Indian Ocean Dipole (IOD) is characterized by the Dipole Mode Index (DMI), which is defined as the difference in monthly SST anomalies averaged between the tropical western Indian Ocean (50°E–70°E, 10°S–10°N) and the tropical southeastern Indian Ocean (90°E–110°E, 10°S–0°). | psl.noaa.gov/data/timeseries/month/ Saji et al. (1999) |
| Northern Hemisphere | AO (dimensionless) | The Arctic Oscillation (AO) index is calculated using EOF analysis of monthly 1000 hPa geopotential height anomalies over 20°N–90°N. The covariance matrix is area-weighted by the square root of the cosine of latitude. The first EOF principal component represents the AO. Monthly indices are obtained by projecting the 1000 hPa geopotential height anomalies onto the first EOF. Following CPC methodology, the index is normalized by the standard deviation of the monthly index (in our work the period is 1991–2020), resulting in a unit variance for the standardized AO time series. | www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/pna.shtml<br><br>www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml |
| | PNA and NAO (dimensionless) | Teleconnection indices for the Pacific–North America (PNA) and North Atlantic Oscillation (NAO) patterns are derived using Rotated Principal Component Analysis (RPCA), following Barnston and Livezey (1987). Standardized 500-hPa geopotential height anomalies (with respect to the 1991–2020 standard deviation) are analyzed separately for each calendar month. For each month, the ten leading EOFs from a three-month window are retained and subjected to Varimax rotation. The rotated EOFs corresponding to the PNA and NAO spatial patterns are then identified. Monthly indices are obtained by projecting the 500-hPa height anomalies onto the corresponding rotated EOF patterns, and subsequently normalized by the standard deviation of the monthly index over the 1991–2020 base period. | https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml Thompson and Wallace (1998) |
| Southern Hemisphere | AAO (dimensionless) | The Antarctic Oscillation (AAO) index is calculated using EOF analysis of monthly 500 hPa geopotential height anomalies over 20°S–90°S. The covariance matrix is area-weighted by the square root of the cosine of latitude. The first EOF principal component represents the AAO. Monthly indices are obtained by projecting the 500 hPa geopotential height anomalies onto the first EOF. Following CPC methodology, the index is normalized by the standard deviation of the monthly index (in our work the period is 1991–2020), resulting in a unit variance for the standardized AAO time series. | https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml Thompson and Wallace (1998) |
| | PSA1 (dimensionless) | Following the same methodology used to calculate the AAO, the Pacific South American (PSA) 1 pattern corresponds to the second EOF principal component. Monthly indices are obtained by projecting the 500 hPa geopotential height anomalies onto the second EOF. The index is normalized by the standard deviation of the monthly index (1991–2020). | https://meteorologia.unifei.edu.br/teleconexoes/indice?id=psa1 Mo and Higgins (1998) |
| | PSA2 (dimensionless) | Following the same methodology used to calculate the AAO, the PSA 2 pattern corresponds to the third EOF principal component. Monthly indices are obtained by projecting the 500 hPa geopotential height anomalies onto the third EOF. The index is normalized by the standard deviation of the monthly index (1991–2020). | https://meteorologia.unifei.edu.br/teleconexoes/indice?id=psa2 Mo and Higgins (1998) |

| | | | |
|---|---|---|---|
| Tropical Band | RMM (dimensionless) | The Real-time Multivariate MJO (RMM) Index is used to monitor the Madden–Julian Oscillation (MJO) following Wheeler and Hendon (2004). It is derived from three daily variables averaged over the equatorial belt (15°S–15°N): outgoing longwave radiation (OLR), and zonal wind at 850 hPa and 200 hPa. Before computing the combined EOF analysis, three preprocessing steps are applied. (a) The mean annual cycle and its first three harmonics are removed from each variable by subtracting the corresponding climatological component at each grid point. (b) The influence of ENSO is removed by regressing out the Niño-3.4 daily index, based on regression coefficients computed for the 1991–2020 base period. (c) Only the intraseasonal variability (periods between 20 and 100 days) is retained by applying a 120-day running mean filter.<br>The standardized anomalies of OLR, u850, and u200 (normalized by their 1991–2020 standard deviations) are then projected onto the first two leading EOFs of the combined anomaly field to obtain the principal components RMM1 and RMM2. The MJO amplitude is defined as the square root of the sum of the squares of RMM1 and RMM2, and the MJO phase is determined by their relative position in phase space. Unlike other EOF-based indices, the RMM index is constructed in real time by projecting the filtered and normalized daily anomalies of OLR, u850, and u200 onto the predefined EOF patterns after the preprocessing steps described above. Finally, RMM1 and RMM2 are standardized by removing their respective climatological means and dividing by their corresponding standard deviations of the daily index over the 1991–2020 base period. | Wheeler and Hendon (2004) |

We chose ERA5 because it employs state-of-the-art 4D-Var data assimilation of extensive in-situ (e.g., 10 m wind over sea and 2 m humidity over land, and pressure over land and sea) and satellite observations with a preliminary product that is available within 5 days of real time, and has demonstrated improvements over previous generations for key atmospheric fields (Hersbach et al. 2020). ERSSTv5 was selected for its homogeneous, basin-scale coverage and documented methodological advances (updated ICOADS/Argo inputs, refined bias adjustments,

**Indices for October 2025**

| AAO | PSA1 | PSA2 | AO | PNA | NAO | DMI/IOD | IOSD |
|---|---|---|---|---|---|---|---|
| -1.07 | -1.47 | 1.16 | 0.53 | -0.62 | -0.73 | -0.92 | -0.74 |

| NINO12 | NINO3 | NINO34 | NINO4 | SOI | TNA | TSA | SASAI |
|---|---|---|---|---|---|---|---|
| -0.30 | -0.45 | -0.53 | -0.40 | 1.41 | 0.40 | 0.04 | 0.33 |

| SSTRG2 | SAODI | SASDI | ONI | QBO | PDO | AMO |
|---|---|---|---|---|---|---|
| 1.03 | -0.18 | -0.32 | -0.45 | -24.65 | -1.21 | 0.99 |

**Indices for November 09th 2025**

| Amplitude MJO | Phase MJO |
|---|---|
| 1.93 | 7.00 |

**Figure 1.** Teleconnection Index Online Tool: summary of the indices.

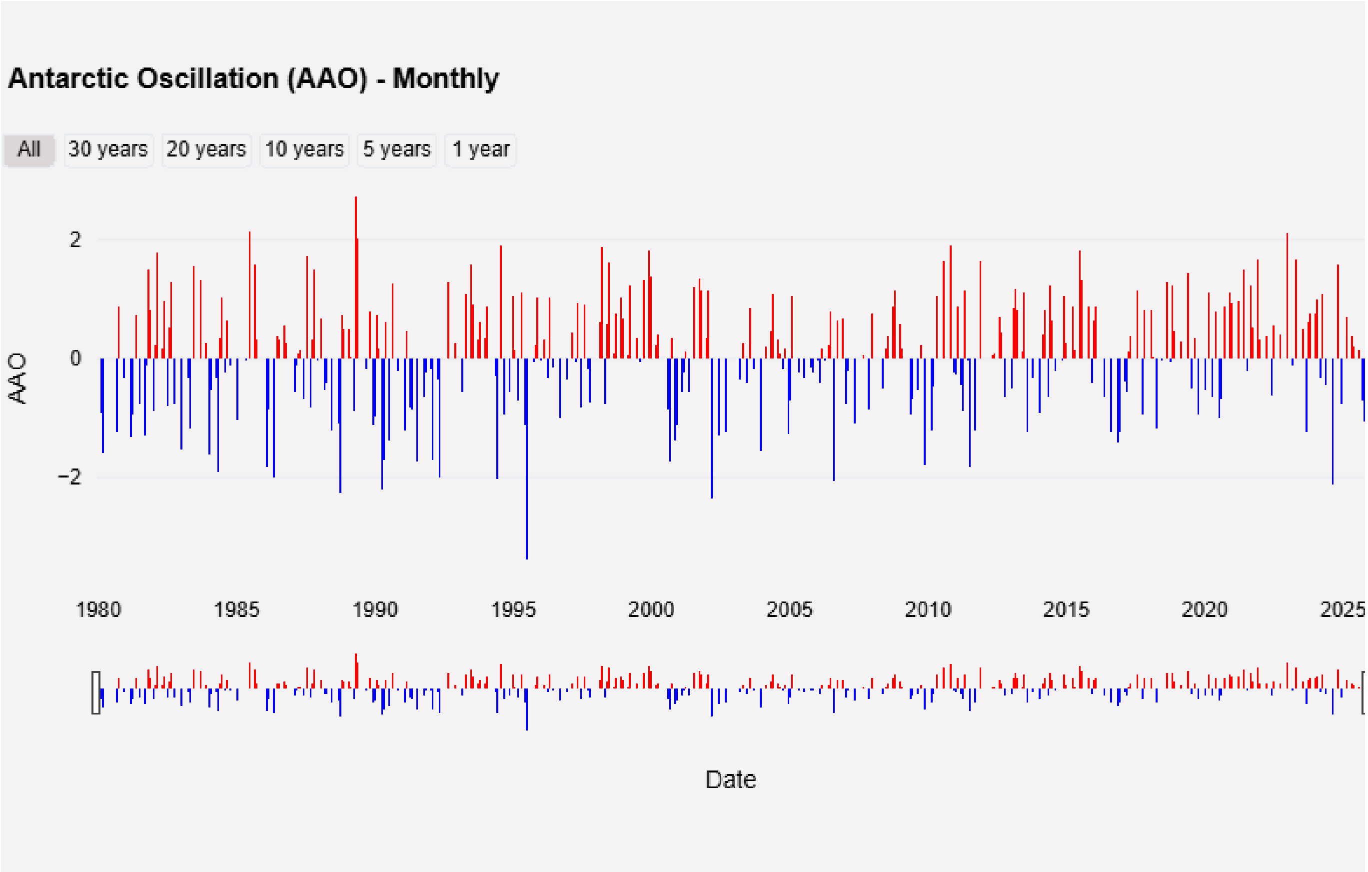


**Figure 2.** Teleconnection Index Online Tool: example of the AAO index time series.

and improved sea-ice treatment), making it well suited to robust computation of teleconnection indices (Huang et al. 2017).

We compute 21 climatic indices on a monthly basis (Table 1), except MJO, which is on a daily basis. Since we are working with gridded data, we first calculate the monthly climatology at each grid point, followed by the monthly anomaly at each grid point. Finally, the anomalies are averaged over the selected region of interest. We did not remove the trend from the data; however, users may choose to detrend the time series if needed.

The online tool also includes four additional indices - Oceanic Niño Index (ONI), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and Quasi-Biennial Oscillation (QBO) - which are based on the ERSSTv5 dataset, except for QBO which is derived from NCEP/NCAR Reanalysis (Kalnay et al. 1996) and not calculated by us but obtained from https://psl.noaa.gov/data/climateindices/list/

### 3. Results and Concluding Remarks

In this paper, we describe the updated version of the teleconnection index online tool, available at: https://app-indice.streamlit.app/. This version is simpler and more streamlined compared to the previous, as we are now computing all indices directly, except for the ONI, PDO, AMO, and QBO.

The first (home) page of the online tool provides a brief description of the data sources and common methodology used to calculate the indices. Additionally, it displays a summary of the indices computed for the previous month (Fig. 1).

In the "Indices" section, the indices are organized into clickable buttons. When a user selects an index, the tool displays the plotted time series (one example for AAO is shown in Figure 2), provides the data in ASCII format, and includes a description of the methodology used to calculate the index.

The indices are automatically updated each month as soon as the ERA5 and ERSST datasets for the previous month become available. In the future, we plan to include a section with predicted indices covering a three-month forecast horizon.

### Acknowledgments

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# The return of equatorial Atlantic extreme events


**Franz Philip Tuchen**

University of Bremen, Bremen, Germany
*Correspondence: fptuchen@uni-bremen.de*


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## 1. Introduction

Extreme sea surface temperature (SST) events in the equatorial Atlantic can cause extended periods of droughts, rainfall, or heatwaves over the surrounding African and South American countries which impacts the lives, property, agriculture, and infrastructure of millions of people living in these areas (Foltz et al. 2019; Rodrigues and Rodríguez-Fonseca, 2022). Recent observations indicate that after a relatively quiet time of almost two decades (Prigent et al. 2020), episodes of extreme ocean surface temperatures might once again be emerging in the equatorial Atlantic.

The equatorial Atlantic warm event of late 2019 (Richter et al. 2022) and the strong Atlantic Niño of 2021 (Lee et al. 2023) marked the start of a new phase of more frequent extreme events in this region. In 2024, a record-breaking warm event was recorded, followed by an abrupt transition to unusually cold ocean temperatures (Tuchen et al. 2025). Most recently, in 2025, observations indicate the development of an extremely cold event in the equatorial Atlantic during boreal summer.

In this communication, we first revisit the origin of extreme events in the equatorial Atlantic and explain why sustained observations and improved understanding of these extreme events are crucial. We then take a closer look at the 2025 cold event and what it might reveal about the changing dynamics of the tropical Atlantic.

## 2. Normal and anomalous changes of SST in the equatorial Atlantic

A typical year at the equator follows a familiar pattern. Early in the year, incoming solar radiation is at its peak as the sun passes directly overhead. By June-August, the sun has shifted northward, solar heating weakens, but more importantly, the winds blow stronger from east to west over the eastern equatorial Atlantic (20°W-0°). Enhanced zonal winds strengthen Ekman divergence and equatorial upwelling. Consequently, the ocean surface cools rapidly due to increased upwelling of colder waters from below and intensified turbulent mixing (Hummels et al. 2014). SSTs generally range from about 28-29°C early in the year and drop to around 24-25°C in boreal summer. This seasonal rise and fall is well known from both satellite observations and measurements from moored surface buoys along the equator (Fig. 1; left panel).

However, the strength of this seasonal cycle may vary from one year to the next. When the surface ocean becomes anomalously warm, it is referred to as a warm event, the most extreme of which are known as Atlantic Niños, drawing an analogy to the El Niño phenomenon in the Pacific Ocean. Conversely, the most pronounced and persistent cold events are referred to as Atlantic Niñas. In short, every Atlantic Niño is a warm event, but not every warm event reaches Niño intensity. The same holds for Atlantic Niñas and cold events. Following the definition of Vallès-Casanova et al. (2020), an event is termed Atlantic Niño or Niña when the 3-month running mean SST anomalies are above 0.5°C or below -0.5°C, respectively, for at least three consecutive months. For instance, the positive anomalies in the summer of 2021 met the criteria for an Atlantic Niño, whereas the negative SST anomalies in the summer of 2024 can be classified as a cold event.

## 3. Extreme events in the equatorial Atlantic impact millions of people

Extreme sea surface temperatures in the equatorial Atlantic have far-reaching impacts on regional and global climate. They influence rainfall over the surrounding continents, tropical cyclone activity, ocean currents and wave dynamics, and even carbon export from the surface layer to the deep ocean.

The location of the tropical rainfall belt, known as the Intertropical Convergence Zone (ITCZ), is strongly tied to where the ocean is warmest. When the equatorial Atlantic is unusually warm, the ITCZ tends to shift toward the equator, leading to reduced rainfall over West Africa, but increased rainfall over Northeastern Brazil and the Gulf of Guinea (Nobre and Shukla, 1996; Rodriguez-Fonseca et al. 2015). Conversely, when the equatorial Atlantic is anomalously cold, the pattern reverses. These shifts can trigger severe droughts or floods,

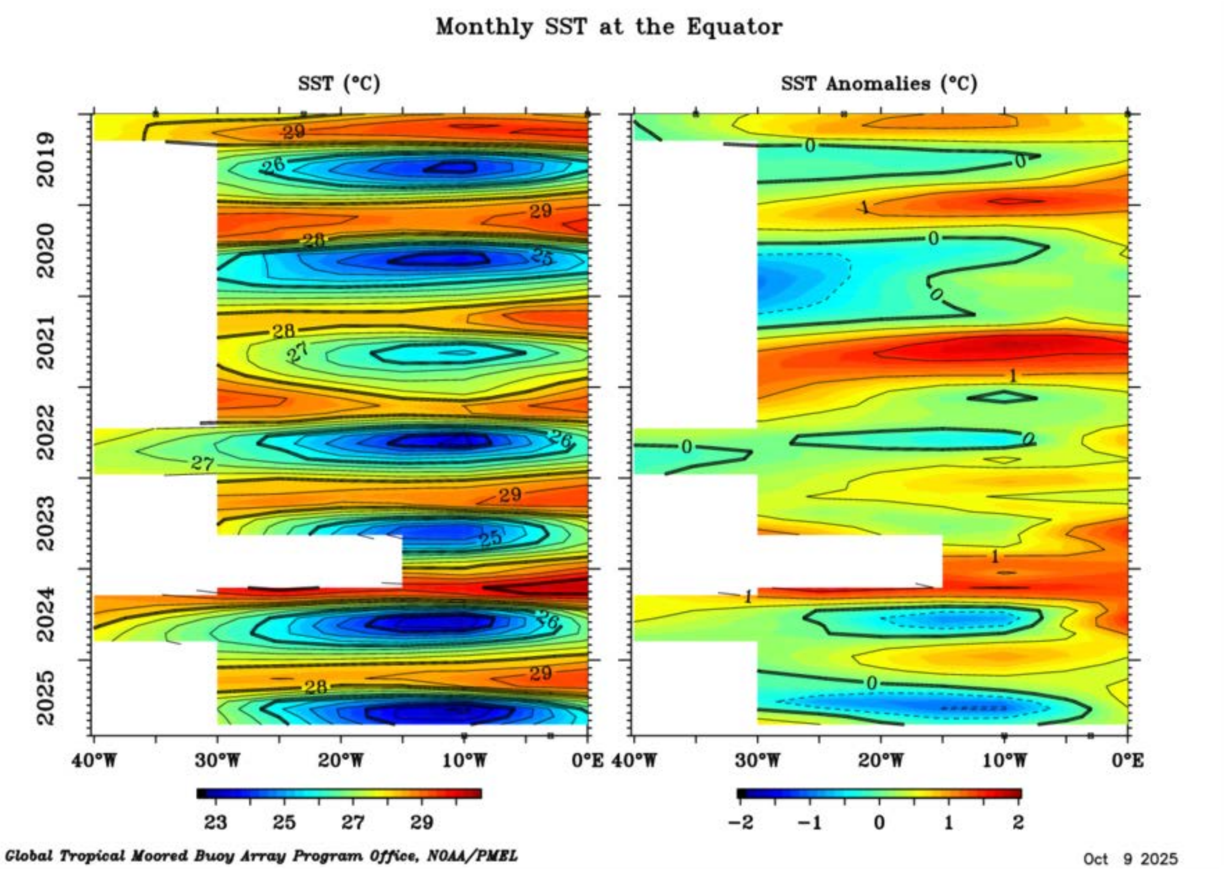


**Figure 1.** Sea surface temperature (left panel) and sea surface temperature anomalies (right panel) along the equator from January 2019 to September 2025, based on measurements from temperature sensors on moored PIRATA buoys at 35°W, 23°W, 10°W, 3°W, and 0°. Under typical conditions, the equatorial Atlantic Ocean warms during boreal spring and cools during summer, but the strength of this seasonal cycle varies from year to year (left panel). Periods with unusually strong departures from the normal cycle (right panel) appear as warm events (2019, 2021, 2024) or cold events (2024, 2025), with the most extreme of these developing into Atlantic Niños or Atlantic Niñas, respectively.

posing significant risks to lives, infrastructure, and agriculture.

Recent research also suggests that extreme SST anomalies in the equatorial Atlantic can affect tropical cyclone activity in the eastern Atlantic (Kim et al. 2023). Atlantic Niño conditions, in particular, may enhance cyclone development near the Cape Verde region, which is an area where many hurricanes that eventually strike the Caribbean or the U.S. originate.

In addition, extreme SST anomalies in the equatorial Atlantic strongly influence local ocean dynamics. They can alter the speed of ocean currents, which in turn affect wave activity and the development of instabilities and mixing along the equator (Tuchen et al. 2024). These temperature anomalies also play a crucial role in regulating the ocean's biological carbon pump. For instance, during the strong Atlantic Niño of 2021, reduced equatorial upwelling led to lower biological productivity and, consequently, reduced carbon export from the surface to the deep ocean during the boreal summer (Habib et al. 2024).

Understanding and monitoring these extreme SST events is therefore essential, not only for anticipating local climate impacts, but also for assessing their broader, indirect influence on the global climate system. For these reasons, it is essential to sustain the tropical Atlantic observing system (Foltz et al. 2019), in particular, the PIRATA moored buoy network (Bourlès et al. 2019). Improved representation of these processes in weather and climate models is essential for developing more accurate and timely forecasts of extreme events. Yet, compared to the Pacific Ocean, where El Niño prediction skill is substantially higher, progress in the Atlantic has been slow and for many years the prediction skill for Atlantic Niño/Niña events did not advance. Recent advances in machine learning, however, offer renewed optimism. Emerging studies demonstrate that deep learning approaches potentially enhance the prediction of Atlantic Niño and Niña events (Bachèlery et al. 2025).

## 4. Recent extreme events in the equatorial Atlantic

As noted earlier, the equatorial Atlantic experienced an extended period of relative calm between 2000 and 2019, with no significant warm events recorded (Fig. 2). The updated time series clearly shows that such events have returned in recent years, highlighted by the warm anomalies of late 2019, summer 2021, and early 2024.

In addition, the data also reveal a marked cold anomaly during the boreal summer of 2025. Even though sea surface temperatures in early 2025 were above average, cold anomalies began to develop in April (Fig. 3). For three consecutive months, from June to August, the equatorial Atlantic Ocean was more than 0.5°C colder than normal, meeting the criteria for an Atlantic Niña. This is the first confirmed cold event since 2013 and, with an

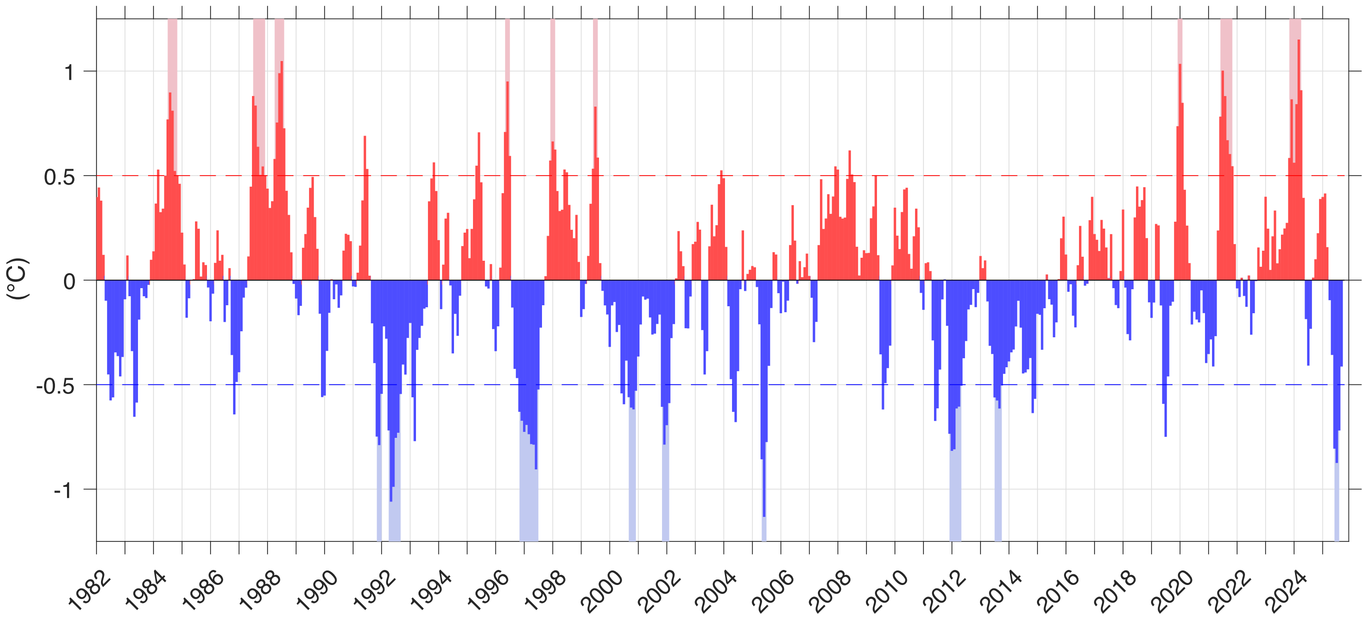


**Figure 2.** Monthly sea surface temperature anomalies in the eastern equatorial Atlantic (20°W-0°, 3°S-3°N; ATL3 region) from January 1982 to September 2025 from satellite observations. Blue bars indicate cold anomalies, red bars warm anomalies. Each value represents a mean of 3 consecutive months. Only if three consecutive mean values exceed the ± 0.5°C threshold (red and blue dashed lines) it is called warm or cold event. Such warm and cold events are marked by red and blue shadings, respectively. The long-term warming trend of 0.75°C between 1982 to 2025 has been removed from the time series.

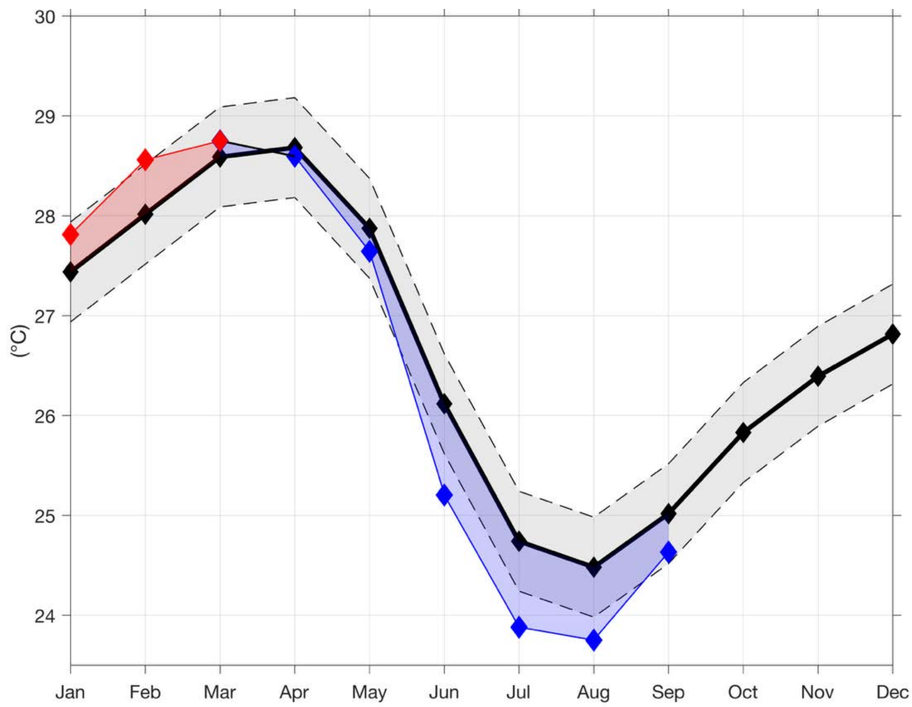


**Figure 3.** Sea surface temperature in the eastern equatorial Atlantic (20°W-0°, 3°S-3°N). The black line and dots show the typical evolution of SST. The dashed line and the grey shading indicate ±0.5°C from the normal condition. The colored line and dots show SST in 2025 so far. Red colors indicate temperatures above normal, blue colors indicate temperatures below normal. June, July, and August were more than 0.5°C colder than normal.

average cold anomaly of -0.83°C between June and August, the strongest Atlantic Niña since 1992 (Fig. 2). Cold SST anomalies during the summer of 2025 were clearly concentrated in the equatorial Atlantic particularly within the ATL3 region (20°W-0°, 3°S-3°N; black rectangle in Fig. 4). We further observe a weakening of the ITCZ, resulting in reduced rainfall of up to 2 mm day-1 over the Atlantic Ocean between the equator and 10°N, as well as in the Gulf of Guinea of up to 1.5 mm day$^{-1}$. Increased rainfall over West Africa and the Sahel region is less pronounced, but is likely an indication of a northward shift of the ITCZ over the African continent.

Interestingly, the winds show a weakening of their typical southeasterly direction during this period. Normally, a stronger zonal temperature gradient during an Atlantic Niña would enhance the zonal winds as part of the Bjerknes feedback (Bjerknes 1969). However, in this case, the opposite occurred which suggests a decoupling between the atmosphere and the ocean, as also observed during the summer of 2024 (https://www.climate.gov/news-features/event-tracker/atlantic-nina-verge-developing-heres-why-we-should-pay-attention).

## 5. Conclusions

While the occurrence of an Atlantic Niña in

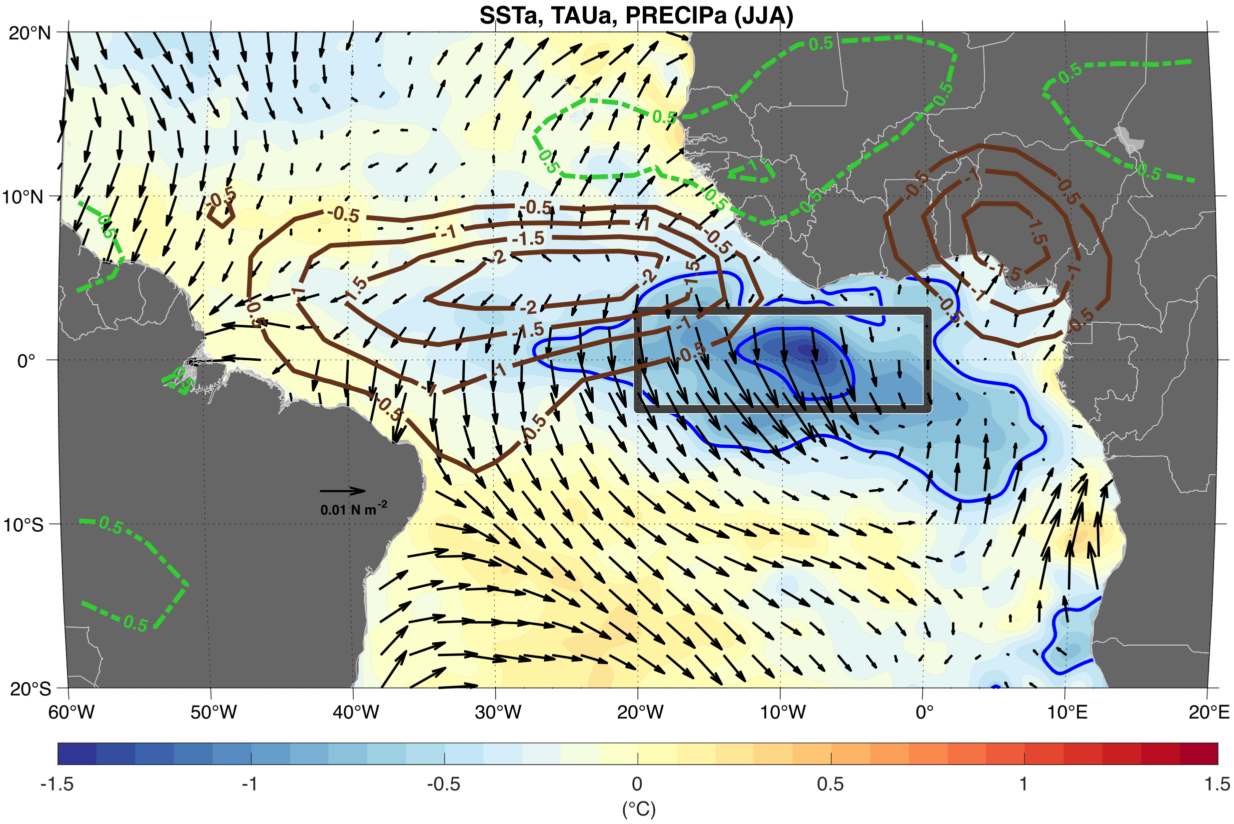


**Figure 4.** Sea surface temperature anomalies in the tropical Atlantic (color shadings), rainfall anomalies (brown and green contour lines; in mm day$^{-1}$), and wind anomalies (arrows) averaged over June-August 2025. Most of the tropical Atlantic has been colder than normal, but the equatorial Atlantic has been extremely cold with anomalies reaching more than -1.0°C. Reduced rainfall is observed over the northern tropical Atlantic and over the Gulf of Guinea. Enhanced rainfall was observed over West Africa and Sahara. Wind anomalies also indicate a northward shift of the ITCZ.

the summer of 2025 is confirmed, scientific understanding of this event remains in its infancy. We are only beginning to investigate its onset, evolution and decay. Preliminary analyses of potential generation mechanisms have not identified a clear key driver for the 2025 Atlantic Niña, and several hypotheses remain under evaluation.

The aim of this communication is to provide a timely summary of the 2025 Atlantic Niña and highlight recent developments in the equatorial Atlantic. The 2025 Atlantic Niña was unusual in several respects.

Key research questions that remain unanswered are not limited to, but include:

-What were the exact mechanisms that triggered the 2025 Atlantic Niña?

-Why did the winds appear to respond to, rather than drive or sustain, the event?

-What factors explain the apparent return to high variability in the equatorial Atlantic after two decades of relative calm?

-Why do we see more extreme events since 2019 during atypical times of the year (outside of boreal summer)?

-Why was tropical instability wave activity (not shown here, but observed at PIRATA moorings) substantially weaker than expected, despite typically being enhanced under cold conditions (Perez et al. 2012)?

Addressing these questions requires sustained, comprehensive observations. Maintaining and strengthening the tropical Atlantic observing system is therefore critical, not only to monitor and understand these events, but also to improve their predictions.

## Acknowledgments

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# UN Ocean Decade Conference Session on Co-Designing Ocean Observing for the Tropics


**Juliet Hermes[1*], JAnn-Christine Zinkann[2,], Weidong Yu[3], Yosuke Fujii[4], Scott Glenn[5], Cheyenne Stienbarger[2], Emma Heslop[6], Gregory Foltz[7], David Legler[2,], Belén Martín Míguez[8], Tammy Morris[1], Ronnie Noonan-Birch[9], Elisabeth Remy[10], Sabrina Speich[11], Anya Waite[9], Hindumathi Palanisamy[12]**

[1] South African Environmental Observations Network, South Africa
[2] NOAA Global Ocean Monitoring and Observing Program, USA
[3] Sun Yat-Sen University, China
[4] Meteorological Research Institute, Japan Meteorological Agency, Japan
[5] Rutgers University, USA
[6] Intergovernmental Oceanographic Commission of UNESCO, France
[7] NOAA Atlantic Oceanographic and Meteorological Laboratory, USA
[8] Global Climate Observing System programme, World Meteorological Organization, Switzerland
[9] Ocean Frontier Institute, Dalhousie University, Canada
[10] Mercator Ocean International, France
[11] Laboratoire de Météorologie Dynamique, France
[12] World Climate Research Programme, World Meteorological Organization, Switzerland
*Correspondence: jc.hermes@saeon.nrf.ac.za*



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Building a transformative and solutions-oriented ocean observing system is critical to the success of the UN Decade of Ocean Sciences for Sustainable Development. The design of such systems should follow the principles of co-design, working with stakeholders across the value chain and integrating their needs into the process. In addition, impact assessments by users such as ocean and climate prediction centers are essential for keeping the ocean observing system effective and efficient. During our satellite event (https://oceandecade-conference.com/on-site-satellite-events.php) held at the UN Ocean Decade Conference in Barcelona, Spain on 11th of April 2024, we discussed these principles and the observational needs of a suite of "exemplars" or user areas with a focus on the tropics. These included boundary currents, tropical cyclones, marine heatwaves and marine carbon which are part of exemplar projects under the Global Ocean Observing System (GOOS) Ocean Decade Co-Design Programme. The event began with a short presentation and was followed by a "speed-dating" session where attendees met with leaders of the GOOS Co-Design exemplars, the coordinating group of the tropical Pacific observing system, and the impact assessing activities from the ocean and climate prediction perspective, to discuss regional involvement and collaborations, and made new connections while raising awareness for the program's activities.

## 1. Ocean Observing Co-Design Program

The Ocean Observing Co-Design Program aims to evolve the ocean observing system to be co-designed with observing, modeling, and key user stakeholders, making it truly responsive and agile to user needs, and integrated along the value chain. This is accomplished through exemplar areas.

### Marine Carbon Exemplar

The carbon exemplar will facilitate a co-design process that produces an expert design for ocean carbon observation in collaboration with end-users. Nations can use this to integrate marine carbon data into climate policies and solutions. During the session, the team engaged with carbon chemists and physical oceanographers to identify the most important measurements for establishing a baseline for ocean carbon. Discussions included a pilot project in the Mediterranean Sea and the impacts of freshwater inputs on acidification. The team also prioritized use cases and explored how regional insights could be scaled globally. This led to discussions on marine carbon dioxide removal (mCDR) and the creation of best practices for carbon data collection, enabling proper monitoring, reporting, and verification.

### Tropical Cyclones Exemplar

Tropical cyclones are among the most significant weather and climate disasters worldwide, causing significant deaths, property damage and economic stress. There is a growing need for improved forecasts to save lives and property, and to improve equity and resiliency. The exemplar aims to co-design ocean observing systems for improving tropical cyclone


*Anya Waite (Carbon Exemplar co-chair) and Ronnie Noonan-Birch from the Ocean Frontier Institute presenting on the Carbon Exemplar Poster*

forecasts and warnings regionally and globally. This is to be achieved by increasing the coverage and delivery of ocean data to forecasting centers and scientists, and increasing connectivity of stakeholders along the value chain. Under the Tropical Cyclone exemplar, five regional pilots have been identified, i.e., the Tropical Americas and Caribbean, North Pacific Ocean and Marginal Seas, Southwest Indian Ocean, the Bay of Bengal, and the Pacific Islands.

Inspired by the recent collaborative, targeted hurricane observations in the Caribbean Sea, the participants discussed the potential collaborative actions across the three tropical basins. The initial interests on the comparative study over the Northwestern Pacific, where the monsoon regime dominates, and the Tropical Atlantic Ocean, where the trade wind prevails, were identified, following up the pan-tropics observing system initiative. This could be further expanded to the tropical Indian Ocean, where the intensive monsoon climate resides. The efforts are expected to improve our understanding on the different life cycles of tropical cyclones over the different climate regimes and their distinctive response to the changing climate.

### Boundary Currents Exemplar

Boundary currents play a crucial role in regional weather systems, marine heatwave and tropical cyclones intensification, and local fisheries and aquaculture. The exemplar focuses on developing an observing system responsive to societal and scientific requirements, fostering innovative science-based solutions. The Boundary Current exemplar has chosen the Agulhas Current as its pilot region given this western boundary current is not well understood, yet is critically important to the global climate system as it connects the Indian Ocean to the Atlantic Ocean. As such, the team organized a workshop (https://goosocean.org/event/4196) to understand priority gaps, develop observational requirements and a draft design of a backbone ocean observing system to better understand key features in the Agulhas Current region that influence critical areas, e.g., Tropical Cyclones, Marine Life, and Marine Heatwaves.

Conversations held during the speed-dating session of the Pan-tropical workshop brought together lessons learnt from other western boundary current systems and in particular, the ocean observing infrastructure that are of value to the understanding of these powerful boundary current systems. One incredibly valuable tool discussed was that of observing system experiments (OSE) and observing system simulation experiments (OSSE) studies, which allows the analysis of an observing system using synthesized observations within a free-run model, or the exclusion of certain data sets, to understand where, in both space and time, observations are most critical to improve model predictions and forecast systems.

### Marine Heatwaves Exemplar

Since the beginning of the 21st century, the particularly rapid warming trend in various oceanic


*Scott Glenn and Cheyenne Stienbarger (Tropical Cyclone Exemplar co-chairs) presenting on a proposed regional pilot at the Korea Institute of Ocean Science and Technology (KIOST)*

regions has been associated with a strong increase in marine heat waves (MHWs). MHWs, defined as prolonged periods of anomalously warm ocean temperatures, have received increasing attention in the last two decades because of their impacts on marine species, habitats (such as seagrass beds, kelp forests, and coral reefs), regional weather regimes, and human societies. The increased frequency, duration and intensity of MHWs is one of the most prominent manifestations of global warming in the oceans. These events can occur not only at the sea surface, but also deeper in the water, posing further ecological risks.

The exemplar aims to develop an observing system capable of responding to different societal and scientific needs related to MHWs that will foster the emergence of innovative science-based solutions. During this session, we were able to discuss how to build the exemplar approach. Indeed, existing research suggests that MHW monitoring should be species-specific rather than geographically based, addressing the specific impacts on different species and ecosystems. However, this approach is complex and challenging given the diverse needs of end-users such as marine ecosystem managers, fisheries and aquaculture, and weather and climate services. To address this, the proposed approach involves co-designing integrated strategies with stakeholders that bridge the gap between scientific metrics and practical MHW indicators. The goal is to improve both surface and subsurface monitoring systems and promote stronger national adaptation strategies to mitigate MHW impacts.

The exemplar will be built in specific regional areas of the Atlantic, Indian and Pacific basins where MHWs already have a strong impact, stakeholder dialogues can be efficiently developed, and observing system strategies guided by OSSEs and OSEs can be synergistically tested.

**2. Pan-Tropical Station**
The team received significant attention from various groups for the pan-tropical approach. The Biogeochemistry (BGC) group expressed interest in the eastern Pacific upwelling region, highlighting the potential for multidisciplinary observation. The Argo group aims to double Argo floats in the tropics and sees pan-tropical observation as complementary to their goals, inviting further interaction at their next meeting. PI-GOOS engagement is essential for the success of pan-tropical observation, and we look forward to deepening this collaboration.

Additional interaction took place with GEOMAR around their initiatives in the tropical eastern Atlantic Ocean, focusing on developing long-term monitoring capacity in the upwelling region. Strong common interests were identified, and further co-development is expected.

**3. NOAA's State of the Ocean Indicators** (https://

stateoftheocean.osmc.noaa.gov/)
One of the other points discussed at the pan-tropics station was NOAA's page on the state of the ocean indicators. There was a suggestion to set up a joint CLIVAR-OOPC pan tropics collaboration to review indices based on updated understandings of inter-basin processes, uncertainty ranges, and the need for observations to reduce uncertainty. This collaboration aims to enhance our understanding and monitoring of oceanic processes across different basins and regimes.

**4. Process and Observation Capability**
An essential aspect of improving our ocean observing systems is understanding how to better observe oceanic and atmospheric processes spanning multiple basins, such as the Indonesian Throughflow (ITF), the Madden-Julian Oscillation (MJO), and El Niño remote forcing. It is crucial to observe common processes across basins and different regimes, such as marine heatwaves, typhoons, cyclones, and hurricanes over trade wind and monsoonal regimes. A key overarching question surrounds the current observational capability for understanding these processes and how it can be improved. This involves engaging coastal countries to fill data gaps around basin boundary regions, evolving the observing system sustainably, and promoting low-cost technology for sustainable observing.

**5. Impact Assessments**
Assessing ocean observation impacts in various application areas are indispensable to secure the funding to sustain the ocean observing system. In particular, the assessment using ocean and climate prediction systems are essential because those are the major applications to make benefits to the general public from ocean observations. Coordinated OSEs using various ocean and climate prediction systems are currently conducted under the UN Ocean Decade project SynObs (https://oceanpredict.org/un-decade-of-ocean-science/synobs-2/) in order to make robust assessments that are not dependent on any particular system. The coordinated OSEs and other SynObs activities were introduced, and the collaboration between the exemplars and SynObs to analyze the OSE outputs and make assessments that meet the needs of both observational and modeling communities was discussed.

**6. Additional Exemplar Areas**
Additional exemplar areas were presented via posters, including Storm Surge and Marine Life, highlighting the broad scope of the Ocean Observing Co-Design Program and its commitment to addressing diverse oceanographic challenges through collaborative, co-designed approaches.

By integrating these discussions and collaborative efforts, we aim to build a robust and responsive ocean observing system that meets the needs of stakeholders and contributes to the sustainable management of our ocean resources.

# The Second Pan-CLIVAR Meeting

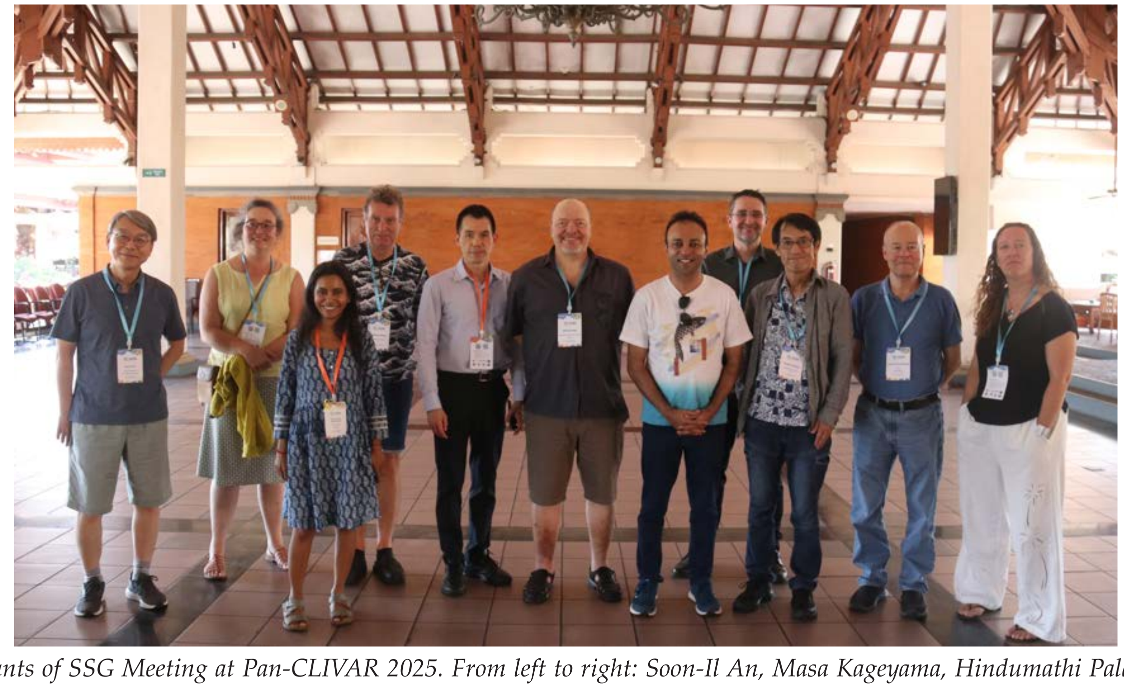
*An event rundown by Agus Santoso on behalf of Pan-CLIVAR 2025 organising committee*

The Pan-CLIVAR Meeting 2025 was held in Bali, Indonesia, from 22nd to 26th of September 2025. Attended by over 150 in-person participants from more than 35 countries, this was only the second Pan-CLIVAR Meeting following the 2014 meeting held in The Hague (https://www.clivar.org/news/first-ever-panclivar-meeting) which was instrumental for the development of the current decadal CLIVAR science plan (2018-2028). The 2025 Pan-CLIVAR Meeting was aimed at initiating the formulation of the next CLIVAR science plan and to mark CLIVAR's 30th anniversary. It included an international symposium themed 'Bridging Science and Society in Southeast Asia and Beyond' (24-25 September).

Details of the event can be found from these websites: pan-clivar2025.sciencesconf.org/, www.clivar.org/events/2025-pan-clivar-meeting.

Pan-CLIVAR 2025 brought together CLIVAR members from all panels, Research Foci (RF), scientific steering group (SSG), guests and representatives from various partner programs and institutions, as well as ocean-climate researchers, professionals, and students who participated in the symposium. Held online and in person at Bintang Bali Resort, Pan-CLIVAR 2025 comprised of plenary sessions, meetings of the SSG, panels and RF, a session on early career researchers, and two side events. The symposium had 12 sessions and 3 CLIVAR capability breakout sessions.

The event began with an SSG-only meeting on the afternoon of Monday 22 September, and was officially opened the next morning. At the opening session, CLIVAR SSG Co-Chair Dr. Gokhan Danabasoglu highlighted the extensive CLIVAR structure and various linkages with external projects, requiring panels and partners to get together to advance progress. World Climate Research Programme (WCRP) Joint Scientific Committee Co-Chair Professor Cristiana Stan elaborated how CLIVAR fits within WCRP as one of the core projects. Representatives of Ocean University of China (OUC) and Laoshan Laboratory (China) that co-host the ICPO: OUC vice president Prof. Houjie Wang, and the Executive Director of the Leading Group for Foreign Affairs of Laoshan Laboratory Dr. Yanheng Xiao, conveyed their congratulatory remarks, stressing the importance of the institutional collaborations with CLIVAR through hosting the ICPO towards understanding of the ocean and climate and societal development. Contributions made by the scientific, event, and local organisers, volunteers and sponsors were acknowledged to make the event possible.



*Participants of SSG Meeting at Pan-CLIVAR 2025. From left to right: Soon-Il An, Masa Kageyama, Hindumathi Palanisamy, Mat Collins, Agus Santoso, Mauricio Mata, Roxy Koll, Francois Engelbrecht, Shoshiro Minobe, Gokhan Danabasoglu, Juliet Hermes*


*Pan-CLIVAR opening featuring Gokhan Danabasoglu (bottom left), Cristiana Stan (middle top), Houjie Wang (middle with Francois Engelbrecht), Yanheng Xiao (top left), Melissa Hart (top right), Chris Lennard (bottom right)*

The opening session concluded with a plenary presentation titled 'Connecting the WCRP Academy and the CLIVAR Community' by Dr. Chris Lennard and Prof. Melissa Hart, co-chairs of the WCRP Academy SSG. A group of participants then stayed on for SSG session on partners engagement, and the rest joined parallel meetings of CLIVAR panels and Research Foci. The SSG session served as a forum for engagement among the various programs and organisations to identify gaps, synergy and cross-cutting issues to sustain and foster collaborations. The panel meetings were attended by several CLIVAR members and invited guests.

Concluding the second day of the event, all participants reconvened in the Ballroom for three plenary presentations by Prof. Fredolin Tangang (University of Brunei Darussalam) on CORDEX

*View of some panel meetings at Pan-CLIVAR 2025*

*Pan-CLIVAR Meeting 2025 participants*

Southeast Asia, Dr. Anna-Lena Deppenmeier (University of Liverpool) on the eastern tropical Pacific sea surface temperature, and Dr. Angela Kuhn (Scripps Institution of Oceanography, pre-recorded) on ocean biogeochemistry parameterisation in Southern Ocean modelling.

On Day 3, the CLIVAR Symposium was opened by Governor of Bali representative, Prof. Anak Agung Suryawan (Udayana University), and was attended by representatives from the Mayor of Denpasar. Following the welcome remarks by Prof. Suryawan was a series of address by WCRP representative Dr. Hindumathi Palanisamy, CLIVAR SSG co-chair Prof. Francois Engelbrecht, the local organising committee members Prof. Ocky Karna Radjasa, chairman of BRIN (National Research and Innovation Agency of Indonesia) Research Organisation for Earth Sciences and Maritime, and Dr. Muh Farid, head of Centre for Coastal and Marine Development at Institut Teknologi Bandung (ITB), and Ning Wang, head of the Cooperation and Planning Department of the Laoshan Laboratory. They overall conveyed the strategic role of the Pan-CLIVAR 2025 for facilitating regional and international science advances in ocean-climate research through the various collaborations fostered at the event.


*Moments captured at the opening plenary of the CLIVAR Symposium*


*Speakers in the CLIVAR Symposium opening session: Prof. Ocky Karna Radjasa (top left), Prof. Anak Agung Suryawan (top centre), Dr. Muh Farid (top right), Prof. Francois Engelbrecht (bottom left), Ms. Ning Wang (bottom centre), Dr. Hindumathi Palanisamy (bottom right)*

The symposium proceeded with Prof. Mat Collins, symposium committee lead, introducing the CLIVAR Symposium and a research topic in Frontiers in Climate journal which was created specifically for the event (https://www.frontiersin.org/research-topics/73794/bridging-ocean-climate-science-and-society-in-southeast-asia-and-beyond). Two keynote presentations concluded the morning session, delivered by Dr. Supari, head of Climate Variability Analysis Division at BMKG (Badan Meteorologi, Klimatologi, dan Geofisika) of Indonesia on El Niño 2023/24 impact prediction, and Dr. Angelique Melet, head of Ocean Climate Team at Mercator Ocean International in France on coordinated regional ocean climate projections.

The symposium continued with three parallel sessions on:

- Atmospheric Processes and Climate Dynamics,
- Ocean-Climate Observations and Modelling,
- Biogeochemical Processes and Climate Interactions,
- Artificial Intelligence: Role in Climate-Ocean Research and Prediction,
- Cascading and Compound Event,
- Climate Variability and Change,
- Ocean Processes and Extremes, and
- Societal Impact.

Poster viewing session held in the afternoon further enriched collegial exchanges among the participants. The symposium had 84 oral presentations and 35 poster presentations, led by 36 conveners from various countries. The day concluded with a cultural Balinese dinner reception.

The symposium continued the next morning for the second part of sessions Climate Variability and Change, Ocean Processes and Extremes, and Societal Impact, followed by three breakout sessions on CLIVAR capabilities: 1) Climate, atmospheric processes, societal impacts, 2) Ocean processes, modelling, observations, biogeochemistry, and 3) Indo-Pacific Ocean, Climate, and Linkage (a PRP-IORP-TBI RF joint-session). These focus breakout sessions were aimed at assessing CLIVAR capabilities and identifying gaps to drive future initiatives. Participants then gathered in the ballroom for a closing plenary where representatives of the breakout sessions summarised their sessions. The symposium which was attended by several world's leading scientists and early career researchers identified advances and research gaps that the community need to tackle to move the science forward and to translate the advances to societal applications.

The rest of the afternoon was occupied by parallel sessions: *Marine Heatwaves (MHW) Open Session, Tropical Basin Interaction (TBI) Open Session, Early Career Research (ECR) Session, and a Side Event: Enhancing International Ocean-Climate Research*

*CLIVAR Symposium participants*

*Collaboration in a Changing Climate.* The MHW and TBI Open Sessions were dedicated to the CLIVAR research focus (RF) groups on the respective topics to provide a forum for interactions between the groups and the wider community. The ECR Session convened by Shikha Singh (IORP co-chair) and Philip Tuchen (ARP member) had presentations from Cristiana Stan (WCRP JSC Co-Chair), Chris Lennard (WCRP Academy SSG Co-Chair), Masa Kageyama (CLIVAR SSG member) and Francois Engelbrecht (CLIVAR SSG Co-Chair) who shared their experiences on opportunities and challenges relevant to ECRs. The side event which was sponsored by the Ocean University of China covered eight topics: OceanObs'29 (Fei Chai), Global Ocean Summit and Global Ocean Research Union (Agus Santoso), sea level rise (Hindumathi Panalisamy), ocean oxygen change and links to heat and carbon (Lijing Cheng), paleoclimate (Jens Zinke, Sujata Murty), ocean observations in Indonesia (Nelly Florida Riama), ocean-climate research collaboration for the Bay of Bengal (Mohan Kumar Das), and 2nd Cooperative

*Participants of Side Event: Enhancing International Ocean-Climate Research Collaboration in a Changing Climate*


*Side Event: Inclusive Innovation for Ocean and Climate Observations which involved a plenary session and surfing sensor app demonstration. Lizzie Murray with Juliet Hermes (top left), Nelly Florida Riama, James Hendy, Faruq Khadami, Lamona Bernawis (top right), Patrick Gorringe (centre), and surfing sensor app demonstration at Kuta Beach.*

Study of the Kuroshio and its Adjacent Regions/ CSK-2 (Xiaopei Lin). Facilitated by Fei Chai, Agus Santoso, Juliet Hermes, and Xiaopei Lin, the side event highlighted the need for collaborations in an increasingly challenging environment.

To celebrate the successful week which was also dedicated for the 30th Anniversary of CLIVAR, participants gathered for dinner reception by Kuta Beach behind the meeting venue which further promoted social interactions among members and guests.

The Pan-CLIVAR 2025 conclusion on Friday 26 September remained filled with engaging scientific activities starting with a plenary session that was aimed to help initiate the next CLIVAR science plan and implementation strategy. The session began with two plenary talks by Nicole Lovenduski (Univ. Colorado Boulder) and Joanna Staneva (Hereon) speaking on Southern Ocean storms' impact on energy and carbon cycling, and Digital Twins of the Ocean, respectively. The plenary session proceeded with CLIVAR panels and research foci representatives to report on key points that came up at their meetings, and concluded with the announcement of the new CLIVAR logo, new ECR Award scheme, and acknowledgments.

Despite the plenary session formally closing the Pan-CLIVAR 2025, the event was programmed to continue into late afternoon with a side event, a closed SSG meeting, and an SSG Open Session. The interactive side event titled 'Inclusive Innovation for Ocean and Climate Observations', was moderated by Juliet Hermes (CLIVAR SSG member) and co-sponsored by Rip Curl Asia. It was opened by Nelly Florida Riama, BMKG leadership and Data Buoy Cooperation Panel (DBCP) Chair, followed by a series of presentations on accessible ocean observing technologies before participants headed out to the beach to demonstrate the technological application through surfing.

Following a closed SSG meeting that was dedicated for discussing partnerships and proposals of new research foci, an open SSG session attended by CLIVAR members and partners was held which managed to gather several points to be considered for the next CLIVAR science plan and implementation strategy.

The Pan-CLIVAR 2025 concluded with reinvigorated energy and friendships among the participants to drive activities for advancing ocean-climate science to the benefit of the environment and society.

*Photographer: Yang Zhao, Di Zhang*

# CLIVAR 30th Anniversary Perspective

**Juliet Hermes**

South African Environmental Observations Network, South Africa

When I was first invited to engage with CLIVAR back in 2009, I was still relatively early in my career and hesitant to step into such a global space. Although I declined formal involvement at that time, I was encouraged and remained deeply interested and continued to follow CLIVAR's work and contributions to ocean-climate science. Looking back now, I realise that this early introduction planted a seed that has grown into a longstanding and meaningful relationship. My first "almost" engagement with CLIVAR was that I was fully funded to attend CLIVAR 2004 in the USA. However, 2 days before I was due to fly I was hit by a car. Luckily that didn't put me off engaging with CLIVAR!

My formal journey with CLIVAR began in 2018 when I joined the Indian Ocean Region Panel (IORP). It was a particularly dynamic and important time, as the panel undertook the IndOOS-2 review, a foundational process that reshaped our understanding and priorities for the Indian Ocean Observing System. From 2021 to 2024, I had the privilege of co-chairing the IORP, first with Roxy Koll and then with Janet Sprintall, both of whom I continue to collaborate with and am privileged to call my friends. Today, I continue to support the panel as an ex officio member, and serve on the CLIVAR Scientific Steering Group (SSG), contributing to the broader vision of the programme.

My connection to CLIVAR, however, goes back further than that. During my early PhD years, I published two articles in CLIVAR Exchanges, both of which were pivotal in developing my scientific identity and voice:

- Hermes, J., C. J. C. Reason, and J. R. E. Lutjeharms, 2002: Inter-ocean fluxes south of Africa in an eddy-permitting model. *CLIVAR Exchanges*, **25**(7).
- Hermes, J., C. J. C. Reason, and J. R. E. Lutjeharms, 2006: Modelling the variability of the Greater Agulhas Current System. *CLIVAR Exchanges*, **39**(11).

More recently, I contributed to the 2020 CLIVAR Exchanges special issue linked to OceanObs'19:

- Hermes, J., N. D'Adamo, L. Beal, R. Koll, N. Hardman-Mountford, E. Heslop, Y. Masumoto, and M. J. McPhaden, 2020: IndOOS, the Indian Ocean Regional Panel and OceanObs19. *CLIVAR Exchanges*, **78**, DOI: 10.36071/clivar.78.2020.

I'm currently involved in the Marine Heatwaves (MHW) Research Focus, and continue to represent the Global South perspective within CLIVAR. Events such as the CLIVAR/GOOS Trieste Workshop in 2022 – *From Global to Coastal: Cultivating New Solutions and Partnerships for an Enhanced Ocean Observing System in a Decade of Accelerating Change* – have demonstrated how far we've come in strengthening global coordination across systems, regions, and communities.

### *CLIVAR at 30: A Celebration of Purposeful Science and Evolving Inclusion*

As CLIVAR marks its 30th anniversary, it is both a moment of reflection and a time for renewed commitment. Over the past three decades, CLIVAR has remained at the forefront of advancing our understanding of ocean-atmosphere interactions and climate variability—from seasonal to centennial timescales. It has been instrumental in promoting integrated observations, improved modelling, and collaborative science across all ocean basins.

Importantly, CLIVAR has evolved with the times. We've seen greater emphasis on early career scientist participation, a stronger presence of researchers from the Global South, and enhanced coordination with complementary programmes such as GOOS, and the UN Decade of Ocean Science. These developments reflect not only an expanding science agenda, but also a deepening recognition that diverse voices and regional knowledge are essential to understanding and responding to global climate challenges.
CLIVAR's community-driven panels and research foci have offered a platform for oceanographers, meteorologists, modellers, and observationalists to come together and shape the trajectory of climate science. For me, this community has provided support, inspiration, and a space to contribute meaningfully to the advancement of science and global observing systems, particularly in the Indian Ocean.

One of the most rewarding aspects of my involvement in CLIVAR has been the deep relationships formed along the way. The CLIVAR community has become more than just a network of colleagues, it feels like a family. Over the years, I've had the privilege of working with brilliant, generous, and inspiring people from across the globe who have not only shaped my science, but also become trusted collaborators and dear friends. This sense of shared purpose and mutual support is one of CLIVAR's greatest strengths, and it's what keeps so many of us engaged and motivated to continue contributing to its mission.

As we look ahead, I remain hopeful and excited for what CLIVAR will continue to catalyse: transformational, inclusive, and collaborative science that supports resilience in a changing climate.

Here's to the next 30 years of CLIVAR, bridging oceans, connecting communities, and driving science that matters.

## *In Memoriam*

## Professor Stefan Hastenrath and Development of Theory of Climate

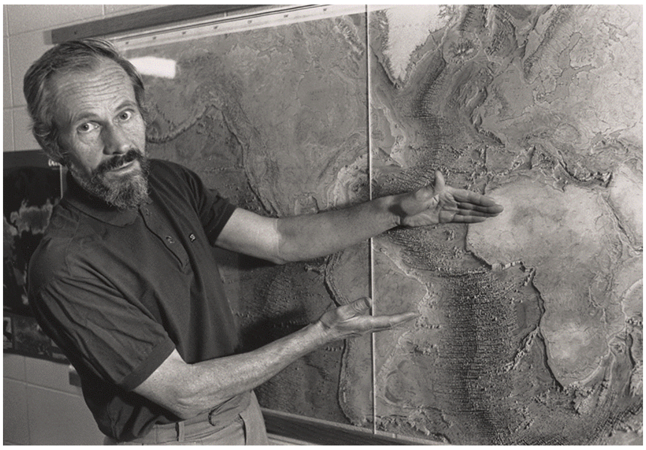
This short paper devotes to an outstanding scientist in the field of Theory of Climate and unique personality, Professor Stefan Hastenrath who passed away in March 2025. This memorial paper is dedicated for the jubilee issue of the CLIVAR Exchanges, especially as Professor Hastenrath's works were cited in the first Science Plan of the CLIVAR Program which was published 30 years ago in August 1995 (The CLIVAR Science Plan 1995).

Let's remind the principal life and career steps of Professor Hastenrath. His parents were from Germany but he was born (in 1934) and passed his children's and youth years in the capital of Hungary (Budapest). Taking into account the origin of Professor Hastenrath, it is very naturally that he graduated from the University of Bonn and obtained the PhD degree at this University. It happened when he was 25 years old. The title of his thesis was "*On the vertical distribution of frost cycle and snow cover conditions in the Alps*" and the study of the snow cover conditions and evolution of the high-altitude glaciers in warming climate became one of his lovely scientific themes till the last years of his life. During 1960-1963, Stefan Hastenrath was Chief of the Climatology Division in the National Meteorological Service of El Salvador. Then he moved to the USA (state Wisconsin) where he worked (mostly at the University of Wisconsin–Madison) till his retirement in 1999. Last quarter century of his life Stefan was the Professor Emeritus at the University of Wisconsin–Madison (Department of Atmospheric and Oceanic Sciences 2025).

Professor Hastenrath received a few pioneer and outstanding results in Meteorology, Climatology, Oceanography and Glaciology, and became one of the most respectable expert in the field of Theory of Climate. First of all, Stefan was the internationally recognized expert in Meteorology and Climatology. Around 70% of his publications were focused to this field. However, I'd like to put attention to the fact that he also had a few pioneer results in Physical Oceanography. For instance, he was one of the first researchers who revealed the quasi-stationary cross-equatorial heat transport in the Atlantic Ocean (Hastenrath, 1980) and the significant Atlantic response to the Pacific El-Niño events (Hastenrath 1978, 1984; Hastenrath and Curtis 1995). Stefan also developed the theoretical base for the one of the first forecasts of the regional climate variations which put into consideration the sea surface temperature as one of the principal predictors (Hastenrath 1976, 1978, 1984, 1991; Hastenrath and Curtis 1995). He always considered the Oceans, Atmosphere and Glaciers as the elements of the joint coupled climate system (Hastenrath 1978, 1991; Hastenrath and Heller 1977).

Stefan has published around 200 influential papers and 15 atlases, monographs and book chapters (selected examples are in the References). The publications of Professor Hastenrath have been cited 8,747 times [www.researchgate.net], while his personal D-index (i.e., Discipline H-index) is 64 (www.research.com). Certainly, this is only formal metric, but it is very remarkable. It is absolutely naturally that after his retirement Stefan was nominated and received the prestigious Sverdrup Gold Medal from the American Meteorological Society. It happened in 2001.

Besides his outstanding scientific results, it is worth to emphasize that personally Stefan was unique and sometimes very unusual man. He was real polyglot and was fluent in dozen languages (German, English, French, Spanish, Dutch, Portuguese, Italian, Hungarian, Greek, Turkish, etc.) and could effectively



*Professor Hastenrath explains the background processes of the Tropical Atlantic seasonal-to-interannual variability (the photo is adopted from In Memoriam: Stefan Hastenrath (Department of Atmospheric and Oceanic Sciences 2025))*

communicate almost with everybody in most of the countries he worked and travelled. In addition, he was very friendly and curious person who was able to establish contact with people of different nationalities and social status.

Professor Hastenrath supervised 21 M.S. and 10 Ph.D. students at the University of Wisconsin–Madison, but his educational activity was much more extended than the lectures, courses, and student supervision given at the university. For a long time, he gave different lectures at numerous colloquiums, seminars and conferences in the various countries using his deep knowledge in the field of Theory of Climate. The broad spectrum of his scientific interests, and ability to speak different languages made these lectures very popular in each auditorium.

The CLIVAR community has lost an outstanding, with unique personality, world-class scientist.

By *Alexander Polonsky*, a colleague and friend of Stefan

A. Polonsky

Scientific Head of the Institute of Natural and Technical Systems of Russian Academy of Sciences (INTS of RAS), Head of Department of Monitoring and Theory of Climate of Sevastopol State University, Professor and Corresponding Member of RAS and National Academy of Sciences of Ukraine; *299011*

*Sevastopol, 14 Gogol str., the Crimea, INTS of RAS; e-mail: apolonsky5@mail.ru*

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# Obituary: Dr Howard Cattle

*A repost from https://www.clivar.org/news/obituary-dr-howard-cattle*

We are saddened to hear of the passing away of Dr. Howard Cattle, Director of the International CLIVAR Project Office (ICPO) from 2002 to 2010 while it was at the National Oceanography Centre, Southampton, UK.

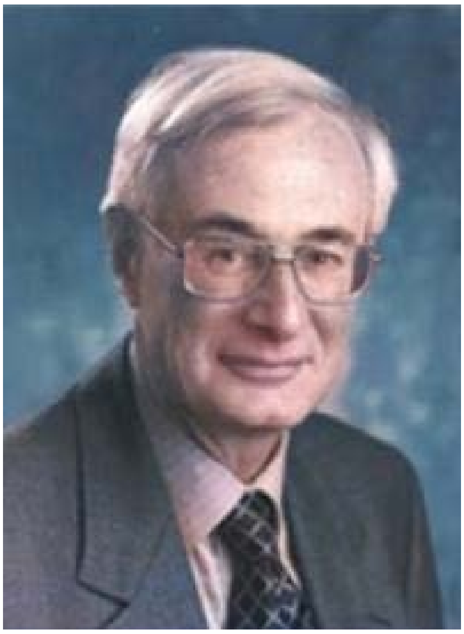
Howard succeeded John Gould in August 2002, as the fourth director of the ICPO, around the time when the World Ocean Circulation Experiment (WOCE) programme was coming to an end. One of the major CLIVAR events under Howard's responsibility was the very first International CLIVAR Science Conference held in Baltimore USA (June 21-25, 2004). The conference was a huge success with 640 registered attendees from 56 countries, providing a comprehensive overview of progress in CLIVAR science over the past 5 years.

Howard's success at the ICPO is highlighted by the account of his successor Dr Robert Molinari during the Director transition (CLIVAR Exchanges 15, No.4, July 2010): Howard has established a level of professionalism that will be difficult (more likely impossible) to achieve… Howard's continued involvement in CLIVAR extended beyond his original retirement date of 31 March 2010 and is a measure of his dedication to the program.

On CLIVAR and the World Climate Research Programme (WCRP), Dr Valery Detemmerman (ICPO Director 2014-2017) adds: "From a WCRP perspective, Howard worked diligently to connect CLIVAR to the broader WCRP community. Sometimes he referred to this as "herding cats", an activity that his Coon cat-breeding household had made him an expert in."

We are indebted to Howard for his hard work as ICPO director during his term, contributing to the success of CLIVAR for the many years that followed.

Prior to taking up the position at ICPO, Dr Howard Cattle had a long and decorated career at the UK Met Office. He joined the Met Office in 1973 as a Senior Scientific Officer working in forecasting research, developing methods for 4-D data assimilation, and was then promoted to Principal Scientific Officer (1975) working on physical parameterisations. In 1976, he became Deputy Principal of the Met Office College that trained new graduate entrants, and was



*Dr Howard Cattle*

transferred to the Dynamical Climatology Branch in 1980 to head a new research group on modelling of the oceans and sea ice. He was involved in establishing the Hadley Centre for Climate Prediction and Research and in 1996 he became the Met Office's Head of Ocean Applications responsible for the Met Office's programme in ocean modelling for short term ocean forecasting, seasonal forecasting and climate prediction. He received his BSc in physics, University of London 1967, and a PhD in Meteorology, Imperial College 1971 (CLIVAR Exchanges 24, June 2002). He was the President of the Royal Meteorological Society from 2002 to 2004.

Our thoughts are with his family and many friends.

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# CLIVAR Exchanges

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Contact:
Director, ICPO
Ocean University of China,
238 Songling Road, Laoshan District
Qingdao 266100.China.
icpo@clivar.org
http://www.clivar.org

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