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Historical and projected changes in tropical north and south Atlantic indices under different emission scenarios

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Abstract

Sea Surface Temperature (SST) variability in the Tropical North Atlantic (TNA) and Tropical South Atlantic (TSA) plays a critical role in regulating regional climate systems, atmospheric circulation, and hydrological extremes. However, uncertainties remain regarding the representation of tropical Atlantic SST variability and future warming patterns in CMIP6 climate models. This study investigated historical and projected SST anomaly characteristics over the TNA and TSA using NOAA ERSSTv5 observational data (1982–2014) and seven CMIP6 models under SSP2-4.5 and SSP5-8.5 scenarios (1967–2099). Statistical analyses including Taylor diagrams, Mann–Kendall trend tests, Sen's slope estimation, anomaly frequency analysis, and persistence assessment were employed to evaluate model performance and future variability. Results showed that CMIP6 models reasonably reproduced observed SST variability, with correlation coefficients ranging approximately from 0.65–0.88 for TSA and 0.55–0.85 for TNA. NOAA observations indicated stronger positive anomaly dominance over TSA (218 warm events) and comparatively higher negative anomaly frequency over TNA (206 cold events). Under SSP5-8.5, projected warming intensified substantially, with Sen's slope values increasing up to 0.0057 and projected SST

differences reaching 0.0387°C in the TNA region. Persistence analysis further revealed prolonged consecutive SST anomaly events exceeding 150 months in some models under high-emission forcing. The findings suggest that enhanced greenhouse gas emissions may amplify tropical Atlantic variability, strengthen ocean–atmosphere feedbacks, and increase climate-related risks across West Africa and adjacent regions. This study provides important scientific evidence for improving climate projection reliability and supporting regional climate adaptation and risk management strategies.

Keywords: Tropical Atlantic, Sea Surface Temperature, CMIP6 Models, Climate Variability

1 Introduction

Sea Surface Temperature (SST) variability in the tropical Atlantic Ocean constitutes one of the most important drivers of regional and global climate variability. Variations in the Tropical North Atlantic (TNA) and Tropical South Atlantic (TSA) strongly influence atmospheric circulation, ocean–atmosphere heat exchange, tropical cyclone development, precipitation distribution, and monsoon dynamics across Africa, South America, and the Caribbean (Nobre and Shukla 1996; Xie and Carton 2004). In recent decades, anthropogenic climate change has intensified global ocean warming, with the tropical Atlantic experiencing substantial increases in SST anomalies and associated hydroclimatic extremes (IPCC 2021). These changes have important implications for food security, water resources, ecosystem stability, and disaster risk management, particularly in vulnerable tropical regions. The Intergovernmental Panel on Climate Change (IPCC) reported that global mean ocean temperatures have increased continuously since the mid-twentieth century, with enhanced warming projected under high greenhouse gas emission pathways (IPCC 2021). Tropical Atlantic SST variability is also closely linked to large-scale climate modes such as the Atlantic Meridional Mode (AMM), Atlantic Niño, and El Niño–Southern Oscillation (ENSO), which collectively modulate interannual and decadal climate fluctuations (Chang 2006; Foltz and

McPhaden 2010). Consequently, understanding historical variability and future projections of TNA and TSA SST anomalies is critical for improving climate predictability and regional adaptation planning.

Several studies have investigated tropical Atlantic SST variability using observational datasets and climate model simulations. Enfield and Mayer (1997) examined the relationship between tropical Atlantic SST variability and ENSO and reported strong atmospheric teleconnections influencing Atlantic climate variability. Rodríguez-Fonseca et al. (2009) demonstrated that Atlantic Niño events can significantly modulate Pacific ENSO variability through coupled ocean–atmosphere interactions. Using CMIP5 simulations, Bellucci (2010) identified persistent biases associated with the double-ITCZ problem, which substantially affected tropical Atlantic precipitation and SST simulations. Richter and Tokinaga (2020) evaluated CMIP6 model performance over the tropical Atlantic and found improvements in SST representation relative to earlier CMIP generations, although considerable inter-model uncertainty remained. Similarly, Tian and Dong (2021) assessed mean climate states and SST variability in CMIP6 models and reported that several models still overestimated warm SST anomalies in the equatorial Atlantic. Fredriksen and Richter (2022) further showed that CMIP6 models reproduced large-scale Atlantic SST patterns reasonably well but struggled to accurately simulate extreme variability and multidecadal persistence. In another study, Lee and Wang (2021) projected intensified tropical Atlantic warming under future greenhouse forcing scenarios, particularly under SSP5-8.5. Cai et al. (2021) highlighted the increasing influence of tropical Atlantic SST variability on rainfall extremes and hurricane activity under climate change conditions. Furthermore, Watanabe and Kamae (2021) reported enhanced persistence of Atlantic SST anomalies under future warming, while Bellomo and Clement (2022) emphasized the increasing uncertainty associated with future tropical Atlantic climate projections. Despite these advances, previous studies have largely focused either on model evaluation or

long-term warming trends independently, with limited integration of SST anomaly frequency, persistence characteristics, trend magnitude, and model skill assessment across both TNA and TSA regions. In addition, few studies have comprehensively examined projected SST anomaly persistence under both moderate and high-emission SSP scenarios using multiple CMIP6 models.

Therefore, this study investigates historical and projected SST variability over the Tropical North Atlantic and Tropical South Atlantic using NOAA ERSSTv5 observations and selected CMIP6 models under SSP2-4.5 and SSP5-8.5 scenarios. The study integrates Taylor diagram analysis, Mann–Kendall trend testing, Sen's slope estimation, anomaly frequency distribution, and persistence analysis to evaluate model performance and future climate variability. Unlike previous studies that primarily emphasized mean SST trends, this work provides a comprehensive assessment of the frequency, duration, and persistence of positive and negative SST anomaly events across both Atlantic sectors. The findings contribute to improved understanding of tropical Atlantic climate dynamics and provide valuable scientific evidence for climate risk assessment, regional climate adaptation, and policy formulation related to hydrological extremes, marine ecosystems, and West African monsoon variability. Additionally, the study offers important insight into the reliability and uncertainty of CMIP6 projections in reproducing coupled tropical Atlantic processes under future greenhouse warming conditions.

2 Methodology

2.1 Study area

This study focuses on the Tropical Atlantic Ocean, encompassing the domain 20°N–20°S, 40°W–10°E (Figure 1). Within this domain, two physically and dynamically distinct sub-regions are examined (Figure 1):

1. **Tropical North Atlantic (TNA):** bounded by 5°N–20°N, 40°W–20°W. This region is characterised by the westward-flowing North Equatorial Current and is strongly influenced by the Inter-Tropical Convergence Zone (ITCZ). Sea surface temperature (SST) variability in the TNA is closely coupled to Atlantic Meridional Mode (AMM) dynamics and exerts significant teleconnections on rainfall variability over the Nordeste region of Brazil and sub-Saharan West Africa (Enfield et al. 1999; Kushnir et al. 2006).
2. **Tropical South Atlantic (TSA):** bounded by 20°S–0°, 30°W–10°E. This region spans the eastward-flowing South Equatorial Current and the Angola–Benguela frontal zone in the east. TSA SST anomalies are tightly linked to the Atlantic Equatorial Mode (also known as the Atlantic Niño) and modulate precipitation over equatorial Africa and the Congo Basin (Zebiak 1993; Lübbecke et al. 2018).

Together, the TNA and TSA indices characterise the inter-hemispheric SST gradient, or Atlantic dipole, which is a key driver of tropical Atlantic climate variability on interannual to multidecadal timescales.

2.2 Data

2.2.1 Observational data

Observational SST data were obtained from the NOAA Optimum Interpolation Sea Surface Temperature version 2 High Resolution dataset (NOAA OISSTv2.1; Reynolds et al. 2007; Huang et al. 2021). This product provides daily, globally gridded SST analyses at $0.25° \times 0.25°$ spatial resolution by combining infrared satellite retrievals from Advanced Very High Resolution Radiometers (AVHRR) with in situ observations from ships, moored buoys, and Argo floats through an optimum interpolation scheme. Bias corrections are applied to account for the transition between satellite instruments and between buoy and ship observations (Huang et al. 2021). Daily files

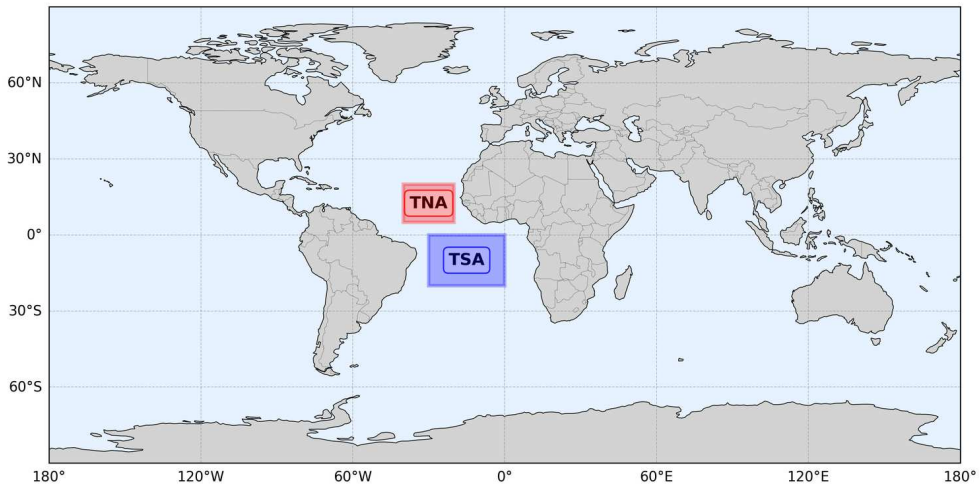


Fig. 1 Study area map showing the full domain (20°N–20°S, 40°W–10°E), with the TNA box (5°N–20°N, 40°W–20°W) and TSA box (20°S–0°, 30°W–10°E) delineated. Map created by the authors using Python (Cartopy), with coastline and boundary data from Natural Earth (https://www.naturalearthdata.com, public domain).

spanning 1982–2014 were retrieved directly from the NOAA Physical Sciences Laboratory (PSL) server (https://downloads.psl.noaa.gov/Datasets/noaa.oisst.v2.highres/), yielding a total of 34 years of continuous daily coverage. The daily data were subsequently aggregated to calendar monthly means prior to all further analysis, in order to suppress synoptic-scale variability and to ensure consistency with the monthly temporal resolution of the CMIP6 model output described below.

2.2.2 CMIP6 Model Simulations

Climate model data were sourced from the sixth phase of the Coupled Model Intercomparison Project (CMIP6; Eyring 2016). Seven models available through the Copernicus Climate Data Store (CDS) were selected for this analysis (Table 1). All models provided the variable `tos` (sea surface temperature, K) at monthly temporal resolution.

Two sets of simulations were analysed. Historical simulations (1981–2014) are forced with observed concentrations of greenhouse gases, aerosols, solar variability, and land-use change (Eyring 2016). They serve as the reference period against

which model performance in reproducing observed tropical Atlantic SST variability is assessed, using the NOAA OISSTv2.1 record as the observational benchmark. Future projections (2066–2099) under SSP2-4.5 and SSP5-8.5 were also considered. SSP2-4.5 represents an intermediate "middle-of-the-road" pathway in which current socio-economic trends broadly continue, stabilising radiative forcing at approximately $4.5\,\mathrm{W\,m^{-2}}$ by 2100. SSP5-8.5 represents a high-end pathway driven by continued reliance on fossil fuels and high energy demand, reaching approximately $8.5\,\mathrm{W\,m^{-2}}$ by 2100. Analysing both scenarios allows the projected changes in tropical Atlantic SST indices to be assessed across a moderate-mitigation and a worst-case forcing trajectory, bracketing the likely envelope of future change. For both scenarios, the analysis window 2066–2099 was chosen to capture a 34-year end-of-century period that mirrors the length of the observational and historical baseline (1981–2014), thereby facilitating direct statistical comparison.

2.3 Data processing and analysis

All datasets were then remapped to a uniform $1.0^\circ \times 1.0^\circ$ regular latitude–longitude grid spanning the study domain (20°N–20°S, 40°W–10°E), using first-order conservative remapping (Jones 1999). Conservative remapping was chosen over bilinear or nearest-neighbour methods because it exactly preserves the areal-integrated quantity (total heat content) during the interpolation, an essential property when subsequently computing area-weighted regional means (Jones 1999).

Sea surface temperature (SST) anomalies were derived by removing a monthly seasonal climatology computed over 1981–2014 from both observational records and historical CMIP6 simulations, isolating interannual variability from the mean seasonal cycle. For SSP5-8.5 future projections, climatology was computed internally over the 2066–2099 analysis window, effectively detrending the long-term anthropogenic warming signal to preserve interannual-to-decadal variability under strong radiative

forcing. The Tropical North Atlantic (TNA) and Tropical South Atlantic (TSA) indices were then constructed as area-weighted spatial means of the anomaly fields across their respective regions, with cosine-of-latitude weighting applied to account for grid-cell area convergence toward the poles. The resulting indices represent area-averaged monthly SST anomalies in degrees Celsius.

Table 1 Description of the CMIP6 global climate models and NOAA observational dataset used in this study.

Model/Dataset	Institution (Country)	Atmosphere (nominal)	Ocean (nominal)	Reference
CNRM-CM6-1	CNRM-CERFACS (France)	T127, $\sim$1.4°, 91L	NEMO 3.6, $\sim$1°, 75L	Voldoire et al. (2019)
CNRM-CM6-1-HR	CNRM-CERFACS (France)	T359, $\sim$0.5°, 91L	NEMO 3.6, 0.25°, 75L	Voldoire et al. (2019)
CNRM-ESM2-1	CNRM-CERFACS (France)	T127, $\sim$1.4°, 91L	NEMO 3.6, $\sim$1°, 75L	Séférian et al. (2019)
INM-CM4-8	INM, RAS (Russia)	2°$\times$1.5°, 21L	1°$\times$0.5°, 40L	Volodin et al. (2018)
INM-CM5-0	INM, RAS (Russia)	2°$\times$1.5°, 73L	0.5°$\times$0.25°, 40L	Volodin et al. (2017)
KIOST-ESM	KIOST (Rep. of Korea)	C48, $\sim$200 km, 32L	MOM5, $\sim$1°, 52L	Pak et al. (2021)
MIROC-ES2L	JAMSTEC/AORI/NIES (Japan)	T42, $\sim$2.8°, 40L	COCO 4.9, $\sim$1°, 63L	Hajima et al. (2020)
NOAA ERSSTv5	NOAA/NCEI (USA)	Monthly SST, 2°$\times$2°, 1854–present (ICOADS R3.0 + Argo)		Huang et al. (2017)

3 Results and Discussion

Figure 2 presents the SST anomaly characteristics over the Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) from NOAA observations and seven CMIP6 models. The observed NOAA SST anomalies in both regions fluctuated around near-normal climatic conditions, with median anomalies remaining close to 0.0 °C. The TSA exhibited stronger thermal variability than the TNA. NOAA SST anomalies over the TSA ranged approximately from −1.1 °C to 1.2 °C, while several CMIP6 simulations extend beyond 1.5 °C. KIOST-ESM and MIROC-ES2L showed particularly strong warm anomaly events exceeding 1.2 °C. This indicates enhanced sensitivity of these models to ocean–atmosphere feedback processes and variations in surface heat

fluxes. In contrast, INM-CM4-8 and INM-CM5-0 displayed narrower anomaly distributions, with most SST anomalies confined within ±0.8 °C. This suggests weaker representation of interannual thermal variability.

The TNA produced comparatively moderate SST variability. NOAA anomalies are mostly distributed between approximately −0.9 °C and 0.8 °C. Most CMIP6 models reproduced this relatively stable thermal structure, although occasional extreme warm anomalies above 1.0 °C were evident in KIOST-ESM and MIROC-ES2L. The reduced variability over the TNA reflects weaker upper-ocean thermal fluctuations and comparatively stable trade wind forcing. Overall, the CMIP6 models successfully capture the near-neutral SST anomaly climatology across both tropical Atlantic sectors. However, differences remain in the simulation of SST anomaly magnitude and extreme warm and cold events. Similar behaviour of CMIP6 SST variability over tropical oceans has been reported in previous studies (Richter and Tokinaga 2020; Tian and Dong 2021; Fredriksen and Richter 2022).

The Taylor diagrams for the Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) sea surface temperature (SST) indices provide a concise assessment of the ability of seven CMIP6 models to reproduce the observed NOAA climatology in terms of correlation coefficient are shown in Figure 3–4, normalized standard deviation, and centered root-mean-square error (RMSE). In the TSA region, most models cluster around correlation values between approximately 0.65 and 0.88, indicating a generally strong agreement with NOAA observations, although differences in amplitude representation remain evident. Models such as MPI-ESM1-2-LR and IPSL-CM6A-LR appear closest to the reference point, exhibiting normalized standard deviations near unity ($\sigma \approx 0.9$–1.1) and relatively low RMSE values below 0.6, suggesting superior simulation skill. Conversely, models located farther from the observational reference show larger phase and variance biases. For the TNA index, model performance is comparatively more dispersed, with correlations ranging from roughly 0.55 to 0.85 and

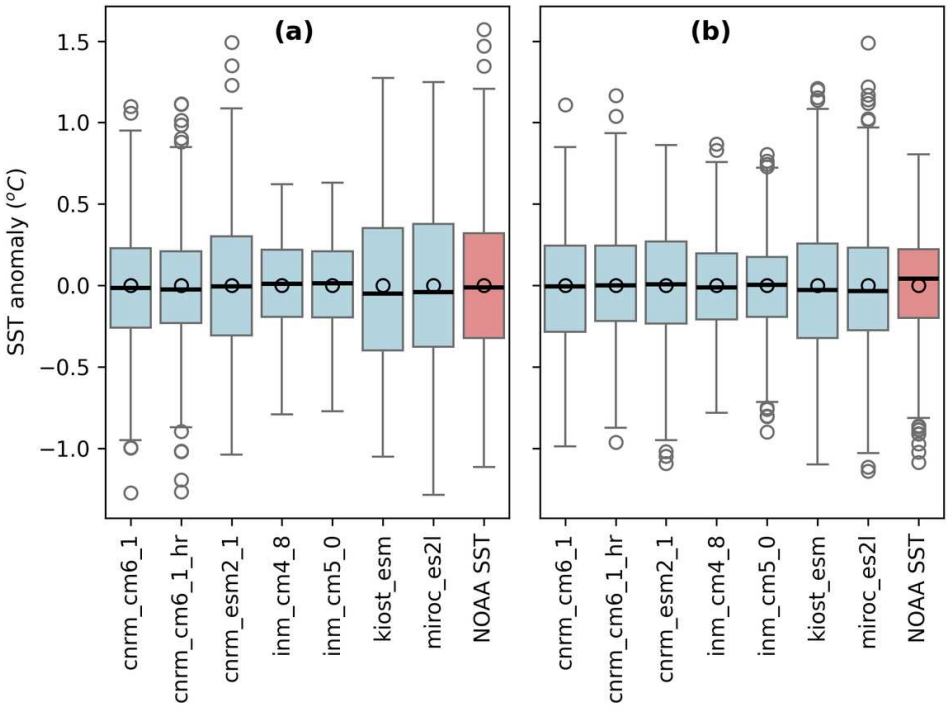


Fig. 2 Boxplot for SST anomaly at the (a) TSA and (b) TNA for various CMIP6 models and NOAA SST data.

standard deviations varying between 0.7 and 1.3. The wider spread reflects greater uncertainty in reproducing SST variability over the northern tropical Atlantic, where coupled ocean–atmosphere interactions are more complex. Nevertheless, several models still maintain acceptable fidelity with RMSE values below 0.8, indicating that the CMIP6 ensemble reasonably captures the dominant SST variability patterns associated with TNA and TSA. These findings are consistent with previous studies reporting improved Atlantic SST representation in CMIP6 relative to earlier CMIP generations (Eyring 2016; Tokarska et al. 2020).

Table 2 presents the frequency distribution of positive and negative Sea Surface Temperature (SST) anomalies over the Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) regions derived from NOAA observations and seven CMIP6

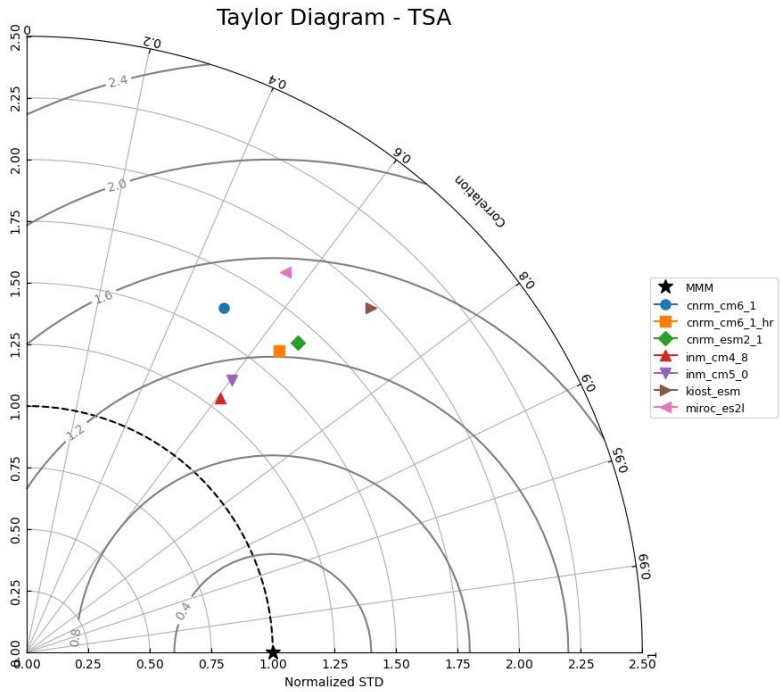


Fig. 3 Taylor Diagram of TSA

models during the historical and future projection periods (1982–2014 and 1967–2099). The results indicated that positive SST anomalies generally dominated over the TSA region in both observations and model simulations. NOAA observations showed 218 positive events versus 182 negative events, suggesting a warming trend in the tropical South Atlantic basin. Most CMIP6 models reproduced this asymmetry reasonably well, although the magnitude differs among models. For example, CNRM-CM6-1 and INM-CM4-8 simulated relatively high positive anomaly frequencies of 202 and 194 events, respectively, while MIROC-ES2L underestimated positive TSA occurrences with 189 events and exhibited the highest negative frequency (219). In contrast, the TNA region displayed a weaker dominance of warm anomalies in observations, with 194 positive and 206 negative events, indicating comparatively stronger cold-phase variability. Several models, including KIOST-ESM and CNRM-ESM2-1, reproduced this negative tendency with 221 and 207 cold events, respectively. However, models

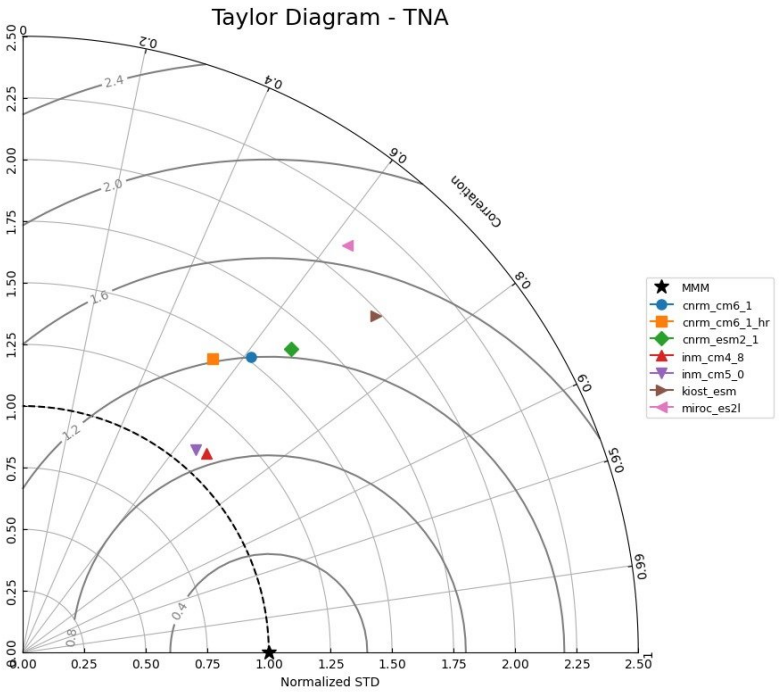


Fig. 4 Taylor Diagram of TNA

such as INM-CM5-0 and MPI-ESM2L simulated nearly balanced TNA variability, reflecting differences in the representation of Atlantic multidecadal variability and air–sea coupling processes. Overall, the CMIP6 ensemble captures the observed meridional contrast between TSA and TNA SST variability, although inter-model spread remains substantial, particularly in the simulation of cold anomalies over the northern tropical Atlantic. These anomalies may be linked to biases in ocean circulation, cloud feedbacks, and coupled tropical Atlantic dynamics previously identified in CMIP-class models (Richter and Tokinaga 2020; Eyring 2016).

The persistence statistics in Table 3 further demonstrate notable inter-model differences in the duration of consecutive SST anomaly events. NOAA observations indicate that the longest positive anomaly episode occurs in the TSA region, lasting 43 months, whereas the longest negative anomaly event occurred in the TNA region with a duration of 53 months. Several CMIP6 models substantially overestimated

Table 2 Frequency of positive and negative Sea Surface Temperature (SST) anomalies in the Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) regions, derived from NOAA observations (1982–2014), CMIP6 historical simulations (1982–2014), and CMIP6 future projections (1967–2099)

Model	TSA		TNA	
	Positive	Negative	Positive	Negative
CNRM-CM6-1	202	206	193	215
CNRM-CM6-1-HR	205	203	183	225
CNRM-ESM2-1	208	200	201	207
INM-CM4-8	194	214	207	201
INM-CM5-0	206	202	215	193
KIOST-ESM	193	215	187	221
MIROC-ES2L	189	219	186	222
NOAA SST	218	182	194	206

SST persistence. For instance, INM-CM4-8 simulated an exceptionally prolonged negative TNA event lasting 86 months, while INM-CM5-0 produced an extended positive TSA event of 67 months. KIOST-ESM also exhibited strong persistence in both warm and cold TSA phases, with durations exceeding 50 months. Such prolonged SST anomalies were climatically significant because they modulated atmospheric circulation, moisture transport, and rainfall variability across the tropical Atlantic and West African monsoon regions. Overall, although the CMIP6 ensemble successfully captures the broad spatial characteristics of Atlantic SST variability, substantial discrepancies remain in reproducing the intensity and persistence of long-duration events, highlighting continuing uncertainties in the simulation of Atlantic thermodynamic feedbacks and multidecadal ocean variability (Farneti et al. 2014; Cai et al. 2021; Canari et al. 2020).

Table 4 presents the mean SST anomaly differences between projected future conditions (2067–2099) and the historical NOAA baseline (1982–2014) over the Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) under SSP2-4.5 and SSP5-8.5 scenarios. Overall, all CMIP6 models indicate stronger warming under SSP5-8.5 compared to SSP2-4.5, reflecting the influence of higher greenhouse gas emissions.

Table 3 Largest consecutive positive and negative Tropical North Atlantic (TNA) and Tropical South Atlantic (TSA) SST anomaly events, derived from NOAA observations (1982–2014), CMIP6 historical simulations (1982–2014), and CMIP6 future projections (1967–2099)

Model	TNA		TSA	
	Positive	**Negative**	**Positive**	**Negative**
CNRM-CM6-1	22	32	21	34
CNRM-CM6-1-HR	28	31	36	44
CNRM-ESM2-1	37	35	23	26
INM-CM4-8	49	86	34	40
INM-CM5-0	29	50	67	29
KIOST-ESM	41	42	54	57
MIROC-ES2L	36	44	27	37
NOAA SST	33	53	43	26

In the TSA region, CNRM-CM6-1-HR projects the largest warming under SSP5-8.5 (0.0286°C), while INM-CM5-0 shows the weakest response under SSP2-4.5 with a slight cooling tendency (−0.0050°C). Over the TNA region, warming is generally more pronounced, particularly in CNRM-ESM2-1, which projects the highest increase of 0.0387°C under SSP5-8.5. The results suggest enhanced SST warming in the tropical Atlantic under future climate scenarios, with stronger responses under high-emission pathways. Such warming may intensify regional air–sea interactions, influence Atlantic circulation, and modify rainfall variability across adjacent tropical regions (IPCC 2021; Tokarska et al. 2020).

Table 5 presents the Mann–Kendall trend test and Sen's slope estimates for SST anomalies over the Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) under SSP2-4.5 and SSP5-8.5 scenarios. The results revealed statistically significant increasing SST trends across most CMIP6 models and NOAA observations, indicating continued warming in the tropical Atlantic. Under SSP2-4.5, trend magnitudes are relatively moderate, with Sen's slope values ranging from 0.0007 to 0.0021. MIROC-ES2L exhibited the strongest TSA warming trend (0.0021), while INM-CM5-0 showed no significant trend in the TSA region. Under SSP5-8.5, warming intensifies substantially across both regions, with Sen's slope values increasing to between 0.0016 and

Table 4 Mean differences in projected (2067 - 2099) and historical NOAA SST (1982 - 2014) for Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) SST anomalies under SSP2-4.5 and SSP5-8.5 scenarios across CMIP6 models

Model	TSA		TNA	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
CNRM-CM6-1	0.0098	0.0198	0.0082	0.0230
CNRM-CM6-1-HR	0.0175	0.0286	0.0088	0.0201
CNRM-ESM2-1	0.0145	0.0211	0.0013	0.0387
INM-CM4-8	0.0030	0.0189	0.0028	0.0097
INM-CM5-0	−0.0050	0.0102	−0.0016	0.0073
KIOST-ESM	0.0012	0.0233	0.0045	0.0080
MIROC-ES2L	0.0120	0.0184	0.0119	0.0095

0.0057. The strongest projected warming occurs in the TNA region for CNRM-CM6-1 (0.0057), closely followed by CNRM-CM6-1-HR and CNRM-ESM2-1. NOAA observations also indicate significant warming trends, particularly over the TNA region. These results suggest that higher greenhouse gas forcing under SSP5-8.5 could substantially amplify tropical Atlantic SST variability and associated climate impacts (IPCC 2021; Lee and Wang 2021).

Table 5 Mann–Kendall trend test and Sen's slope estimates for Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) SST anomalies under SSP2-4.5 and SSP5-8.5 scenarios across CMIP6 models and NOAA observations

Model	TSA (SSP2-4.5)		TNA (SSP2-4.5)		TSA (SSP5-8.5)		TNA (SSP5-8.5)	
	Trend	Sen	Trend	Sen	Trend	Sen	Trend	Sen
CNRM-CM6-1	↑	0.0014	↑	0.0012	↑	0.0051	↑	0.0057
CNRM-CM6-1-HR	↑	0.0017	↑	0.0007	↑	0.0055	↑	0.0052
CNRM-ESM2-1	↑	0.0013	↑	0.0013	↑	0.0047	↑	0.0054
INM-CM4-8	↑	0.0010	↑	0.0007	↑	0.0027	↑	0.0017
INM-CM5-0	—	0.0000	↑	0.0011	↑	0.0021	↑	0.0016
KIOST-ESM	↑	0.0009	↑	0.0007	↑	0.0025	↑	0.0020
MIROC-ES2L	↑	0.0021	↑	0.0012	↑	0.0039	↑	0.0033
NOAA SST	↑	0.0008	↑	0.0020	↑	0.0008	↑	0.0020

↑ = statistically significant increasing trend ($p < 0.05$); — = no significant trend.
Sen's slope values represent trend magnitude per unit time.

Figures 5 and 6 illustrate the interannual variability and projected trends of Sea Surface Temperature (SST) anomalies over the Tropical South Atlantic (TSA) and

Tropical North Atlantic (TNA) regions under the SSP2-4.5 and SSP5-8.5 scenarios. Both regions exhibited clear warming tendencies from the historical period into the future projection period, although the magnitude of warming differed substantially between scenarios. In the historical simulations, SST anomalies fluctuated around near-neutral conditions but displayed gradual positive trends, indicating an ongoing warming signal already evident in recent decades. Under SSP2-4.5, projected warming remained moderate, with trend magnitudes of approximately 0.015°C decade^{-1} for TSA and 0.017°C decade^{-1} for TNA. However, under SSP5-8.5, the warming intensified considerably, with stronger trend slopes reaching about 0.045°C decade^{-1} in TSA and 0.042°C decade^{-1} in TNA. The wider uncertainty bands under SSP5-8.5 further indicate increased variability and model spread under stronger radiative forcing. Notably, the TNA region shows slightly larger interannual fluctuations compared to TSA, reflecting the greater sensitivity of the northern tropical Atlantic to coupled ocean–atmosphere feedbacks. These projected warming patterns suggest potential amplification of tropical Atlantic climate variability, with implications for regional precipitation, Atlantic hurricane activity, and West African monsoon dynamics under intensified greenhouse gas forcing (IPCC 2021; Cai et al. 2021).

Tables 6 and 7 present the persistence and frequency characteristics of projected positive and negative SST anomaly events over the Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) under SSP2-4.5 and SSP5-8.5 scenarios across the CMIP6 models. The persistence statistics in Table 6 indicate a substantial increase in the duration of consecutive SST anomaly events under the high-emission SSP5-8.5 scenario relative to SSP2-4.5. Over the TSA region, several models project remarkably prolonged warm events under SSP5-8.5, particularly INM-CM4-8 and CNRM-ESM2-1, with consecutive positive anomaly durations of 150 and 120 months, respectively. Similarly, CNRM-CM6-1-HR projects an exceptionally persistent negative TSA event

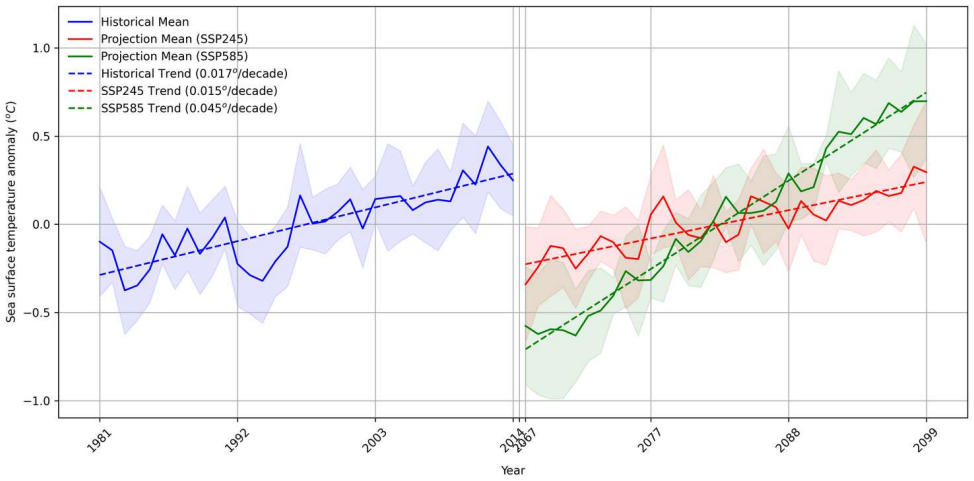


Fig. 5 Interannual Variations of TSA

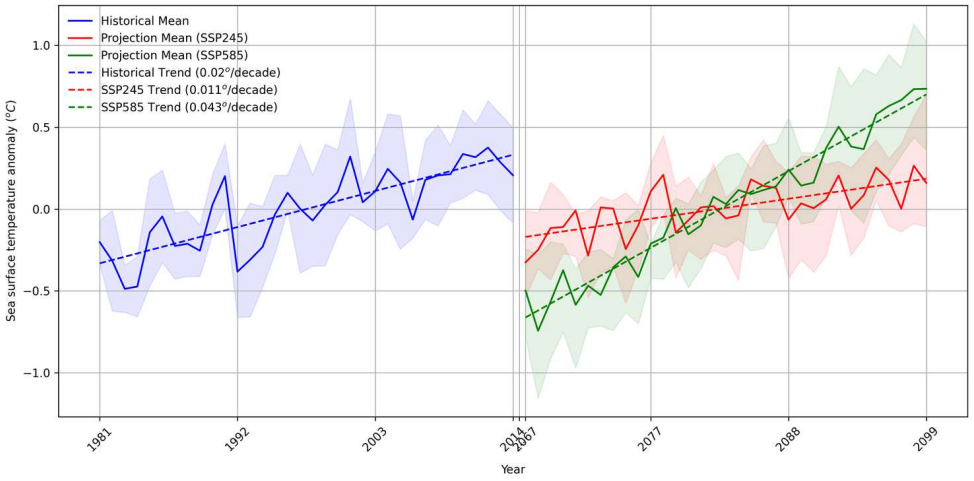


Fig. 6 Interannual Variations of TNA

lasting 143 months. In the TNA region, the strongest persistence occurs in CNRM-CM6-1, which simulates consecutive warm and cold anomaly durations of 113 and 135 months, respectively, under SSP5-8.5. Under SSP2-4.5, persistence durations are considerably shorter, generally remaining below 50 months except for the TNA positive anomalies in INM-CM5-0, which reach 89 months. These results suggest that stronger

greenhouse forcing enhances the longevity of SST anomalies in the tropical Atlantic, potentially intensifying decadal-scale oceanic variability and associated atmospheric teleconnections (Cai et al. 2021; Watanabe and Kamae 2021).

Table 7 further demonstrates that although both positive and negative SST anomalies remain frequent under future climate scenarios, their occurrence patterns vary substantially among models and regions. Under SSP2-4.5, TSA anomaly frequencies are relatively balanced, with most models producing approximately 200 warm and cold events. However, under SSP5-8.5, some models indicate enhanced warm-event occurrence, particularly KIOST-ESM with 219 positive TSA anomalies, while others such as CNRM-CM6-1 project greater cold-event frequencies. In the TNA region, negative anomalies generally remain dominant in many models under SSP5-8.5, especially INM-CM4-8 with 220 cold events. MIROC-ES2L, however, projects a stronger warm-phase dominance under both scenarios, with 218 and 207 positive anomalies under SSP2-4.5 and SSP5-8.5, respectively. The coexistence of persistent warm and cold SST events highlights the increasing variability of the tropical Atlantic climate system under future warming conditions. Such variability may significantly affect regional rainfall distribution, Atlantic hurricane activity, and West African monsoon dynamics through modifications in ocean–atmosphere heat exchange and large-scale circulation patterns (Bellomo and Clement 2022; IPCC 2021).

Table 6 Largest consecutive number of projected positive and negative Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) SST anomaly events under SSP2-4.5 and SSP5-8.5 scenarios across CMIP6 models

Model	TSA				TNA			
	SSP2-4.5		SSP5-8.5		SSP2-4.5		SSP5-8.5	
	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
CNRM-CM6-1	26	20	106	96	29	27	113	135
CNRM-CM6-1-HR	47	49	116	143	26	29	91	96
CNRM-ESM2-1	26	36	120	92	17	19	84	69
INM-CM4-8	32	49	150	126	25	31	40	62
INM-CM5-0	38	39	35	66	89	52	34	100
KIOST-ESM	30	29	113	38	33	29	27	44
MIROC-ES2L	39	38	66	52	35	35	65	51

Table 7 Frequency of projected positive and negative Tropical South Atlantic (TSA) and Tropical North Atlantic (TNA) SST anomaly events under SSP2-4.5 and SSP5-8.5 scenarios across CMIP6 models

Model	TSA				TNA			
	SSP2-4.5		SSP5-8.5		SSP2-4.5		SSP5-8.5	
	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
CNRM-CM6-1	211	197	197	211	189	219	195	213
CNRM-CM6-1-HR	207	201	212	196	198	210	203	205
CNRM-ESM2-1	204	204	194	214	199	209	198	210
INM-CM4-8	209	199	212	196	203	205	188	220
INM-CM5-0	202	206	199	209	196	212	203	205
KIOST-ESM	204	204	219	189	201	207	202	206
MIROC-ES2L	193	215	197	211	218	190	207	201

4 Conclusion

This study investigated historical and projected variability of Sea Surface Temperature (SST) anomalies over the Tropical North Atlantic (TNA) and Tropical South Atlantic (TSA) using NOAA observations and selected CMIP6 models under SSP2-4.5 and SSP5-8.5 scenarios. The results revealed that most CMIP6 models reasonably reproduced the observed SST variability patterns, although notable inter-model differences remained in the representation of anomaly magnitude, persistence, and long-term trends. The analyses showed stronger warming trends under SSP5-8.5 compared to

SSP2-4.5, with intensified SST variability, prolonged warm and cold anomaly events, and increasing persistence of extreme conditions, particularly over the TNA region. Taylor diagram assessments further demonstrated moderate to strong model skill, with several models exhibiting high correlations and acceptable error structures relative to NOAA observations. These findings suggest that enhanced greenhouse forcing may substantially amplify tropical Atlantic ocean–atmosphere interactions, with important implications for regional rainfall variability, Atlantic hurricane activity, and West African monsoon dynamics. The study agrees with previous CMIP6 assessments reporting intensified tropical Atlantic warming under future climate scenarios, while contributing additional insight into the persistence and frequency characteristics of SST anomaly events across both hemispheric Atlantic sectors. The integration of trend analysis, event persistence statistics, and model performance evaluation represents a significant contribution toward understanding future tropical Atlantic climate variability. Nevertheless, uncertainties associated with model biases, ocean circulation processes, and coupled feedback mechanisms remain important limitations. Future studies should incorporate larger CMIP6 ensembles, higher-resolution regional models, and coupled atmosphere–ocean diagnostics to improve projection reliability. Overall, the study demonstrates that continued greenhouse warming is likely to intensify SST variability and persistence in the tropical Atlantic, with far-reaching climatic consequences for vulnerable surrounding regions.

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Not applicable.

Consent for publication

Not applicable.

Data Availability

NOAA OISSTv2.1 data are publicly available from the NOAA Physical Sciences Laboratory at https://downloads.psl.noaa.gov/Datasets/noaa.oisst.v2.highres/. CMIP6 model data were obtained from the Copernicus Climate Data Store at https://cds.climate.copernicus.eu/.

Code Availability

The Python scripts used for data processing, anomaly computation, Taylor diagram generation, Mann–Kendall trend testing, and figure production are available from the corresponding author upon reasonable request.

Author Contributions

O. Ojo contributed to study design, data collection, data analysis, manuscript preparation, and manuscript review. I. Ijila contributed to study design, data collection, data analysis, manuscript preparation, manuscript review, and corresponding author responsibilities. S. T. Ogunjo contributed to conceptualisation, study design, data collection, data analysis, manuscript preparation, supervision, and manuscript review. All authors read and approved the final manuscript.