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Strengthened tropical Pacific influence on tropical Atlantic variability in global warming projections

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ABSTRACT

Projected changes in tropical Atlantic variability are examined by comparing a high-emission scenario (experiment ssp585) with a pre-industrial control simulation (experiment piControl) using an ensemble of 23 climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Consistent with previous studies, equatorial Atlantic sea-surface temperature (SST) variability (the Atlantic Zonal Mode or AZM) decreases, while variability off the equator tends to slightly increase. AZM composites show that in ssp585 the role of dynamic forcing by surface wind stress anomalies is diminished while thermodynamic forcing through latent heat flux and shortwave radiation becomes more prominent. This is related to a stronger influence of El Niño-Southern Oscillation (ENSO) on the AZM. As a consequence, a positive correlation between ENSO and AZM emerges, with the former preceding the latter by about half a year. A simple linear analysis indicates that, in some models, this association of AZM with ENSO makes it more predictable, despite its weakening amplitude. The stronger ENSO influence on the AZM is partly explained by the stronger ENSO amplitude in ssp585. In addition, the weakening of coupled air-sea feedbacks in the equatorial Atlantic makes it more susceptible to ENSO forcing. In contrast to some previous studies, it is found that the mean-state equatorial Atlantic thermocline shoals under radiative forcing, which should strengthen the AZM. Its decline may therefore be more related to other oceanic or to atmospheric mean state changes that weaken coupled air-sea feedbacks.

1. Introduction

The tropical Atlantic features several variability patterns that vary on seasonal-to-decadal time scales (Xie and Carton 2004). Sea-surface temperatures (SSTs) in the equatorial Atlantic are dominated by the Atlantic zonal mode (AZM), a pattern that resembles, to some extent, El Niño-Southern Oscillation (ENSO) and is therefore also sometimes referred to as Atlantic Niño. The typical evolution of a positive AZM event starts with a weakening of the equatorial trades and is accompanied by a southward shift of Atlantic Intertropical Convergence Zone (ITCZ; see Lübbecke et al. 2018, and Richter and Tokinaga 2021 for reviews of equatorial Atlantic variability). The weakened zonal surface winds lead to a deepening of the oceanic thermocline, which in turn renders upwelling-induced cooling less effective, thus leading to SST warming in the eastern equatorial Atlantic. The warm SST anomalies act to further weaken the surface zonal winds, consistent with the Bjerknes feedback in the equatorial Pacific (Bjerknes 1969). In contrast to the equatorial Pacific, however, coupled feedbacks in the equatorial Atlantic are strongly modulated by the seasonal cycle and are mostly active during May and June only (Keenlyside and Latif 2007; Richter et al. 2017; Nnamchi et al. 2022). As a consequence, wind anomalies already start to decay in June and July, when the SST anomalies are most pronounced.

While substantially weaker than ENSO, the AZM can have important influences on rainfall over South America (Nobre and Shukla 1996) and West Africa (Lamb 1978; Folland et al. 1986; Janicot et al. 1998; Giannini et al. 2003; Rodriguez-Fonseca et al. 2011; Mohino et al. 2024), and may also influence ENSO (Rodriguez-Fonseca et al. 2009; Ding et al. 2012), though the strength of this influence remains under debate (Exarchou et al. 2021; Richter et al. 2021; Richter et al. 2023; Jiang et al. 2023; Richter et al. 2024). Some

73 studies suggest that the influence of AZM on ENSO has strengthened in recent decades
74 either because the SST anomaly pattern has shifted toward the western part of the basin,
75 where the higher background SST can amplify the atmospheric response (Zhang et al.
76 2023), or because the warming Atlantic background state amplifies the atmospheric re-
77 sponse regardless of SST pattern (Wang et al. 2024). The influence of ENSO on the AZM,
78 on the other hand, has been found to be inconsistent due to the competing dynamic and
79 thermodynamic influences from the tropical Pacific (Chang et al. 2006), with Richter et al.
80 (2025) suggesting that the timing of ENSO evolution determines the balance between the
81 two mechanisms.

82 Given its important role in the climate system, it is of interest to know how the char-
83 acteristics of the AZM and its interaction with other basins may change under global warm-
84 ing. Investigating the fate of the AZM under increasing greenhouse gas forcing, however,
85 has been hampered by the fact that virtually all global climate models (GCMs) suffer from
86 severe biases in the region (Richter et al. 2008; Richter et al. 2014; Richter and Tokinaga
87 2020). In particular, the eastern equatorial cold tongue, marked by cool SST in boreal sum-
88 mer, is poorly represented in GCMs, which manifests as a severe warm bias. Moreover,
89 there is a pervasive westerly wind bias in the preceding season, as well as an erroneous
90 southward shift of the ITCZ. Notwithstanding these potential obstacles, it has been shown
91 that models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5)
92 and Phase 6 (CMIP6) project a rather consistent weakening of equatorial Atlantic variabil-
93 ity (Crespo et al. 2022; Yang et al. 2022), and that models with a more realistic represen-
94 tation of present-day equatorial Atlantic variability tend to project a more pronounced
95 weakening (Crespo et al. 2022). This weakening of the AZM is thought to result from the

96 stabilization of the atmosphere (Held and Soden 2006; Yang et al. 2022), and the deepening
97 of the thermocline (Crespo et al. 2022; Yang et al. 2022), both of which were assumed to
98 weaken the Bjerknes feedback. The atmospheric stabilization weakens the response of sur-
99 face winds to SST anomalies, while the deeper thermocline insulates the SST from ther-
100 mocline anomalies.

101 On the observational side, Tokinaga and Xie (2011) have shown that both the strength
102 of the equatorial Atlantic cold tongue and the amplitude of the AZM are modulated on
103 multi-decadal time scales, possibly by the Atlantic Multidecadal Variability (AMV), with
104 a recent decrease in variability coinciding with the negative phase of the AMV. Interest-
105 ingly, another observational study by Servain et al. (2014) found a strengthening of the
106 Atlantic trade winds in recent decades, including in the equatorial region, which may not
107 be entirely consistent with the results of Tokinaga and Xie (2011).

108 A weakening of the AZM was also found by a more recent study (Prigent et al. 2020a),
109 while observations from 2019 onward suggest a resurgence of equatorial Atlantic variabil-
110 ity (Richter et al. 2021; Lee et al. 2023; Tuchen et al. 2025).

111 Other tropical Atlantic variability patterns are also expected to be affected by increas-
112 ing greenhouse gas forcing, among them the Benguela Niño (Shannon et al. 1986;
113 Florenchie et al. 2003; see also reviews by Oettli et al. 2021 and Brandt et al. 2024), which
114 is associated with interannual SST variability along the Angola-Benguela upwelling area
115 (ABA). Variability in this region is driven by both coastally trapped waves that are re-
116 motely forced by equatorial wind anomalies (Florenchie et al. 2003; Lübbecke et al. 2010;
117 Illig et al. 2020) and by changes in the local along-shore wind stress driving variations in
118 upwelling (Richter et al. 2010). A study with a single GCM forced by increasing

greenhouse gas concentrations indicates a weakening of ABA variability (Prigent et al. 2023) due to weakening influences from the equatorial Atlantic and to increased stability of the ocean column in the ABA inhibiting upwelling-related SST changes. The former process is consistent with the observed weakening of ABA variability during the period 2000-2017 (Prigent et al. 2020b).

Variability in the northern tropical Atlantic is dominated by the Atlantic Meridional Mode (AMM), which manifests as SST anomalies in the northeastern tropical Atlantic that result from wind-driven changes in latent heat flux (Hastenrath 1984; Nobre and Shukla 1996). A positive feedback between surface wind, evaporation and SST, called the WES feedback, enhances initial SST anomalies and may lead to their equatorward propagation (Xie 1996; Chang et al. 1997; Chiang and Vimont 2004; Kataoka et al. 2019). This variability pattern is projected to increase under rising greenhouse gas forcing due to the strengthening and eastward shift of ENSO, which results in stronger remote forcing from the tropical Pacific via the Pacific North America (PNA) teleconnection pattern (Yang et al. 2021; Geng et al. 2024). There are, however, substantial uncertainties associated with these projections. Hou and Zheng (2025) find a robust intensification of the Pacific Meridional Mode under global warming in CMIP6, but the AMM exhibits no consensus among models. Xia et al (2023) show the simulated wind–SST relationship associated with the AMM varies among CMIP6 models, indicating uncertainty in future AMM behavior under warming. Zhang et al. (2024) show a notable enhancement in tropical North Atlantic SST prediction skill in the high-resolution CESM that stems from a more realistic representation of the AMM and the associated WES feedback, which is closely linked to the improvements in Atlantic ITCZ.

In the present study, we would like to reexamine the influence of global warming on tropical Atlantic variability in climate change projections. Given that previous studies have already examined the climate change response of tropical Atlantic variability, that the variability in question is relatively weak compared to its Pacific counterparts, and that the persistent climate model biases in the tropical Atlantic undermine the credibility of projections for the region, it is a valid question to ask whether deeper analysis is warranted. While the studies by Crespo et al. (2022) and Yang et al. (2022) have found a robust weakening of the AZM in CMIP climate change projections, they left several questions unanswered. One is the extent to which there are qualitative changes in the physical mechanisms that underpin the AZM. The previous studies showed that there are quantitative changes in the dynamic feedback mechanisms, but could there also be qualitative changes or new aspects that emerge? The previous studies also did not examine how remote linkages with other basins might change. In particular, will the role of ENSO change? Finally, what are the implications for predictability? Will the AZM become less predictable in the future? In the present study, we will take a closer look at these aspects not only for the AZM but also for the AMM and Benguela Niño. We will show that, under increased radiative forcing, thermodynamic processes become more dominant, ENSO's influence on tropical Atlantic variability strengthens, and predictability tends to increase.

The rest of the paper is organized as follows. In section 2, we describe the datasets used in this study, the methodology for calculating composites and correlations, and the linear regression model we use to estimate predictability. In section 3, we first examine mean state changes in the tropical Atlantic under global warming (section 3.1), followed by an overview of variability changes in the tropical Atlantic (section 3.2), a closer

examination of changes in the AZM (section 3.3), and a brief look at how the observed decline in AZM variability and its relation to climate simulations (section 3.4). Variability in the northern and southern tropical Atlantic will be examined in sections 3.5 and 3.6, respectively. Changes in the remote linkages of the tropical Atlantic are the topic of section 4, while the predictability changes will be analyzed in section 5. We close with a summary and discussion in section 6.

2. Data and methods

2.1. Observational data and model output

For observational SST, we use the HadISST dataset (Rayner et al. 2003) for the period 1900-2024, while for observation-based SST and near-surface wind, we use the fifth major global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA5; Hersbach et al. 2018) for the period 1979-2024. For ocean temperature, maximum vertical temperature gradient, thermocline depth, and mixed-layer depth we use the ECMWF Ocean Reanalysis System 5 (ORAS5; Zuo et al. 2019). Thermocline depth in both reanalysis and model output is calculated as the depth of the maximum vertical temperature gradient. The mixed-layer depth is determined as the depth where density exceeds surface density by more than 0.03 kg/m^3 .

To study the response of tropical Atlantic variability to greenhouse gas forcing, we use the pre-industrial control simulation (piControl) of the Coupled Model Intercomparison Project Phase 6 (CMIP6) as our reference and compare it against the ssp585 high-emission scenario to obtain the most robust response. Using piControl as our reference also avoids complication of dealing with the spatially and temporally varying aerosol forcing. CMIP6 historical simulations are analyzed in section 3.4, where we discuss the observed decline

in AZM variability during the period 2000-2019. For this analysis, we concatenate the historical simulations for the period 1900-2014 and the ssp585 simulations for the period 2015-2024. For each model, the corresponding historical and ssp585 ensemble members are concatenated, resulting in a time series spanning from 1900-2024 for each ensemble member.

In addition to offering a baseline climate, the piControl experiments also have the advantage of providing long time series under steady radiative forcing, which reduces the risk of long-term trends confounding the analysis of interannual variability. Nevertheless, all fields in piControl are linearly detrended before analysis.

For ssp585 there is an obvious trend in most fields due to the increasing greenhouse gas forcing. In our analysis, we focus on the period 2071-2100, i.e., the final segment of the core integration period. This is again motivated by the desire to maximize the signal. During the 30-year period, trends are linear to first approximation, and we therefore chose to use linear detrending, as for piControl.

2.2. Methods

A substantial portion of our study relies on composite analysis. Since it is difficult to obtain reliable composites from only 30 years of data, we require that the models in our analysis have at least 3 ensemble members available, thus resulting in a minimum of 90 years available for analysis. For consistency, the same set of models is also selected from the piControl experiment. These 23 models are listed in Table S1 of the Supplementary Material.

Lagged regressions form another part of our analysis. For the ssp585 experiment, we again require that at least 3 ensemble members be available. The 3 or more segments are

first linearly detrended and then concatenated to form one continuous time series. Where lagged time steps lie outside a given segment, these values are ignored in the calculation.

Table 1. Definitions of the indices used in this study.

Index Name	Averaging Region	Variable
Niño 3.4	170°W-120°W, 5°S-5°N	SST
ATL3	20°W-0, 3°S-3°N	SST
ATL4	45°W-20°W, 3°S-3°N	10m zonal wind
NTA	80°W-20°W, 10°N-20°N	SST
STA	40°W-10°E, 30°S-10°S	SST
ABA	10°E-coast, 20°S-10°S	SST
AB1	10°E-coast, 25°S-15°S	SST
AB2	10°E-coast, 30°S-0	10m meridional wind

Several climate indices are used in our analysis, and their definitions are listed in Table 1. The Niño 3.4 index is a measure of ENSO variability, while the ATL3 index is a measure of AZM variability. Near-surface wind variability in the equatorial Atlantic is most pronounced in the western part of the basin, which motivates the ATL4 index definition as anomalous 10m zonal wind averaged over the western equatorial Atlantic. The northern tropical Atlantic (NTA) and southern tropical Atlantic (STA) measure SST variability in the subtropical regions, with the former being associated with the AMM. Another index, the ABA, measures the variability associated with the Benguela Niño and is defined as SST anomalies averaged along the coast of southwestern Africa. Benguela Niño variability tends to be shifted poleward in the GCMs, relative to observations (Richter et al. 2014). To take this into account, we define the AB1 index. Furthermore, along-shore winds play some role in the genesis of Benguela Niños (Richter et al. 2010; Illig et al. 2020; Brandt et al. 2024). We therefore define the AB2 index as anomalous meridional 10m wind along the southwest African coast.

To estimate the predictability of the AZM, we use a multi-linear regression analysis relying on some of the SST indices defined above, namely the ATL3, both as predictand and predictor, and the Niño 3.4, NTA, and STA as predictors. In addition, we use the tendency of the Niño 3.4 index, motivated by the study of Richter et al. (2025). A simple cross-validation is performed by using one half of the time series as training data and the other half as test data. Due to the relatively long time series, this is sufficient for reliable estimates. More details can be found in Richter et al. (2025).

2.3. Statistical significance

The evaluation of the significance of differences in multi-model ensemble means (Figs. 1 and 2) follows the IPCC AR6 methodology but with some modifications. In AR6, a difference between two ensemble means is deemed significant and robust if (a) at least 2/3 of the model pairs have differences that are significant at the 90% level according to a two-sided t-test, and (b) at least 80% of the model pairs agree on the sign of the difference. Here, we modify criterion (a) to account for the fact that each value of the ssp585 models represents an ensemble average (with ensemble sizes ranging from 3 to 50, as detailed in Supplementary Table 1). We thus evaluate the significance for each model by using a bootstrapping method in which the piControl field is divided into non-overlapping 30-year blocks and the average of each block is calculated. A random sample of N averages is drawn from these 30-year averages, where N is the number of ensemble members available for a given model in ssp585. The average of the piControl sample is compared with that of the N -member ssp585 ensemble. In some ssp585 models, N is too large to allow for a matching number of N 30-year blocks in piControl. In these we reduce N to N' so that $2*N'*30$ is less than the number of years in piControl, thus ensuring that a sufficient number of random samples can be drawn from piControl. The random sampling is repeated

1000 times and a difference is deemed significant at the 95% level if fewer than 5% of the draws show a larger value. Points for which both criteria (a) and (b) are satisfied are shaded/contoured in Figs. 1 and 3.

For the multi-model mean composites, statistical significance is evaluated using a one-sample t-test at the 95% confidence level. Lagged correlations are tested in a similar manner, using the t-test for Pearson's correlation coefficient.

3. Changes in the tropical Atlantic mean state and its variability

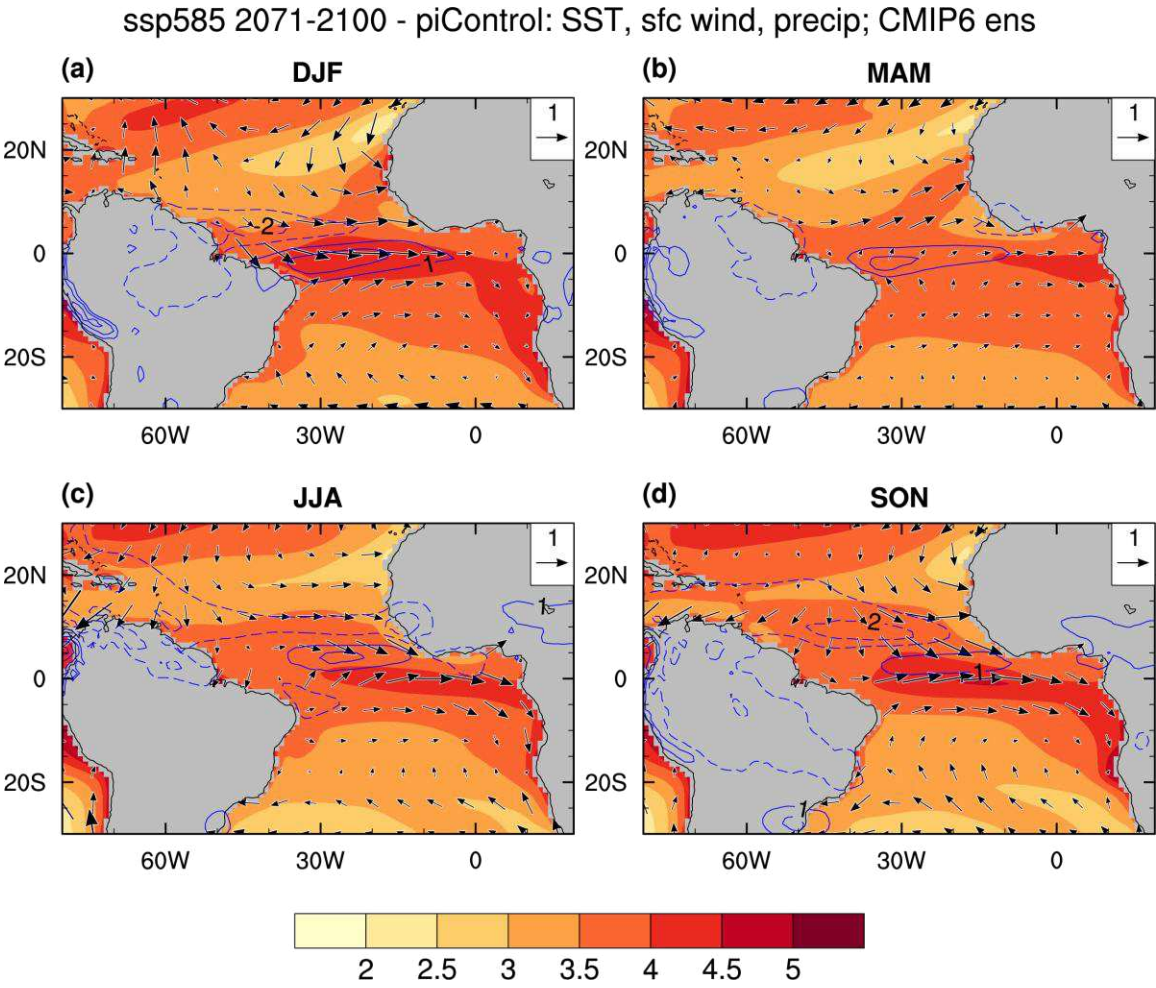
3.1. Mean state changes

Relative to piControl, the ensemble mean SSTs increase by about 2.5 to 4.5 K in ssp585, with the most pronounced warming occurring in the upwelling zones along the equator and the southwest African coast (Fig. 1 and Fig. S1). Lower warming rates are seen in the subtropical oceans. The SST warming patterns show only a weak dependence on season. All values pass the robustness and significance tests.

The equatorial easterlies weaken by about 1 m/s in ssp585 during all seasons except March-April-May (MAM). MAM is the season when the equatorial easterlies are weakest, both in piControl and in observations (Xie and Carton 2004; Richter et al. 2014a; Lübbecke et al. 2018; Richter and Tokinaga 2021). Off the equator and extending to about 15°N and 15°S, the trade winds tend to weaken in the eastern half of the basin. In contrast, the trade winds mostly strengthen poleward of 15°N/S.

The Atlantic ITCZ shifts equatorward in all seasons except MAM (Fig. S1), when it tends to be on the equator in observations (Richter et al. 2017) or south of the equator in piControl (Richter and Tokinaga 2021). Over tropical South America and West Africa,

275 precipitation tends to decrease in ssp585, while over equatorial Africa, there is some in-
 276 crease.



277
 278 **Figure 1.** Climatological differences between CMIP6 experiments piControl and ssp585 for the ensemble
 279 mean over 23 models. The fields shown are SST (shading; K), 10 m winds (vectors; reference vector indicates
 280 1.0 m/s), and precipitation (contours; contour interval is 1 mm/day; dashed contours indicate negative values;
 281 zero-contour omitted). The climatology of ssp585 is calculated using the years 2071 to 2100. The individual
 282 panels show the following four seasonal averages: (a) DJF, (b) MAM, (c) JJA, and (d) SON. Values that do
 283 not pass the significance and robustness criteria are masked out. See section 2.3 for details on the statistical
 284 testing.
 285

The changes in thermocline depth are unexpected (Fig. 2c, d). Both Crespo et al. (2022) and Yang et al. (2022) indicated a deepening of the thermocline in the warming scenarios. Their analysis, however, was based on the depth of the 20°C isotherm (Z20). Our analysis, using the actual thermocline depth, indicates that the thermocline shoals in both the ATL4 and ATL3 regions, even though most of the changes are not significant at the 95% confidence level. Z20 is a relatively good proxy for thermocline depth in the equatorial Pacific but is less well suited for the equatorial Atlantic, where it tends to overestimate thermocline depth (Castaño-Tierno et al. 2018). In addition, the adequacy of Z20 as a proxy for thermocline depth is dependent on the oceanic mean state, which is subject to change under global warming. We will revisit this point in section 3.2.

Comparison with the ORAS5 suggests that the models fail to capture the seasonal cycle of thermocline depth in the ATL3 region (Fig. 2d), in particular the shoaling in boreal summer. In addition, the thermocline tends to be too shallow in the models. This is also the case in the ATL4 region, but the observed seasonal cycle is reasonably well reproduced there (Fig. 2c).

Changes in mixed-layer depth are very small in the ATL3 region (Fig. 2b) but in the ATL4 region there is a shoaling of about 2 to 4 m (approximately 10-15%), except during JJA (Fig. 2a). The maximum vertical temperature gradient consistently increases in both regions (Fig. 2e, f), which is expected from the maximum warming at the ocean surface (cf. Fig. 3 in Crespo et al. 2022).

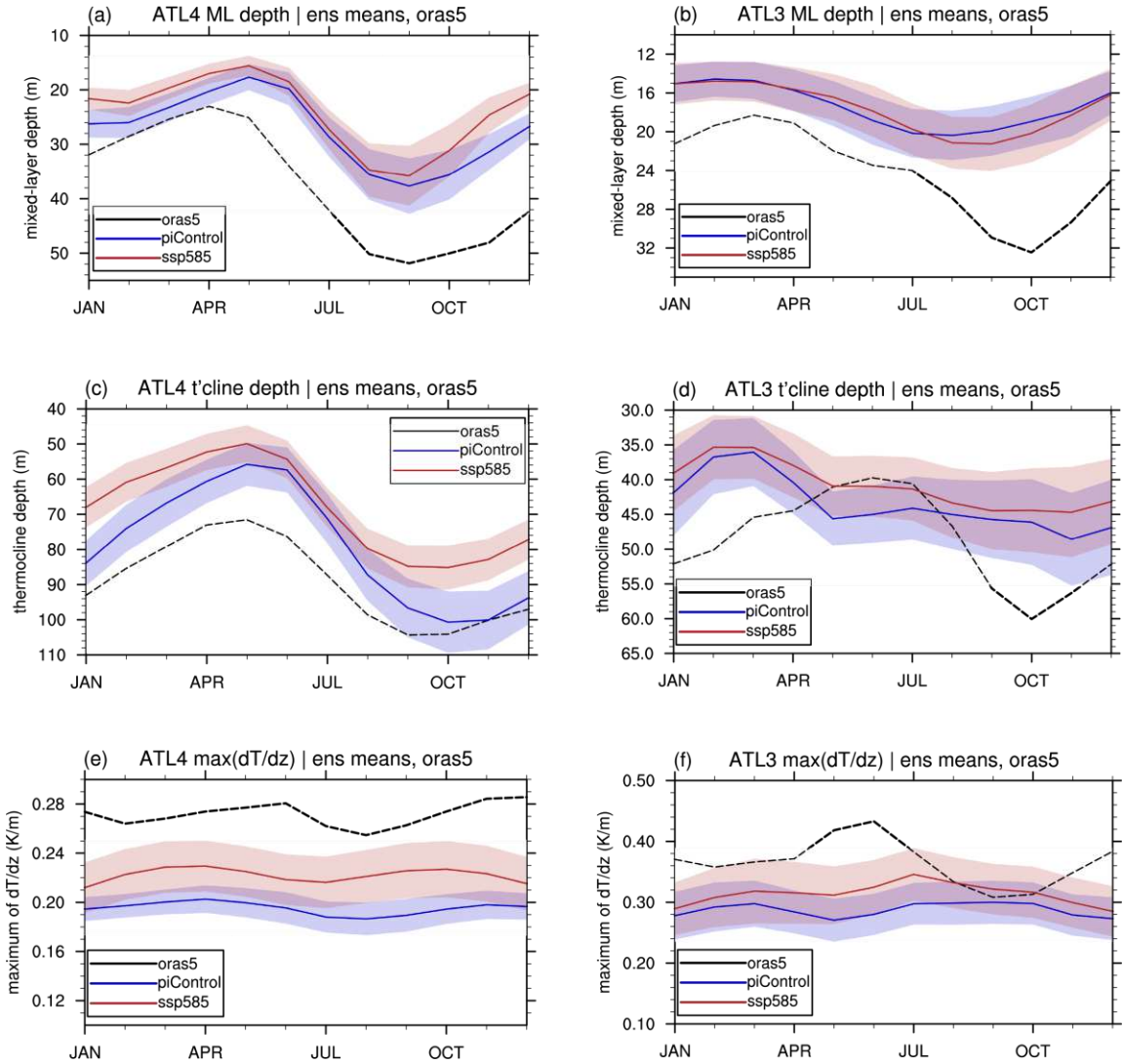


Figure 2. Climatological annual cycle of (a,b) mixed-layer depth (m), calculated as the depth where density is 0.03 kg/m^3 higher than the surface density, (c,d) thermocline depth (m), calculated as the depth of the maximum temperature gradient, and (e,f) maximum vertical temperature gradient (K/m). The dashed black lines show the ORAS5 reanalysis, the blue lines show the piControl ensemble mean, and the red lines show the ssp585 ensemble mean. The light blue and light red shading denote the 95% confidence intervals for piControl and ssp585, respectively. The left and right columns show the area-averages over the ATL4 and ATL3 regions, respectively.

3.2. Changes in variability

SST variability decreases along the equatorial and coastal upwelling regions (Fig. 3 and Fig. S2), contrasting with the increased mean SSTs in these areas (Fig. 1). Crespo et al. (2022) and Yang et al. (2022) noted that Z20 deepens in the eastern equatorial Atlantic under global warming as a consequence of the weakening equatorial trades. From this they concluded that the thermocline also deepens and suggested that this would decrease the impact of upwelling anomalies on SST. However, as we have seen in section 3.1, the thermocline does not deepen in the warming scenario but actually slightly shoals. While a thorough analysis of the heat budget may be necessary to clarify the role of oceanic stratification, our analysis suggests that the reduction in equatorial surface wind variability plays a larger role in the decline of SST variability.

It is interesting to note that the decrease in SST variability is mostly limited to the equatorial and coastal upwelling regions and most pronounced in June-July-August (JJA) and SON. In many other regions, there is an increase in SST variability, even though this increase is not always robust (cf. Fig. S2).

We examine SST variability changes in four regions of interest, namely the ATL3, NTA, AB1, and STA (Fig. 4). Relative to the observations, ATL3 variability in piControl peaks one month late but its amplitude compares well with observations. In ssp585, ATL3 variability decreases from May through December (Fig. 4a), which includes the variability peak of the AZM in JJA and a secondary peak in November and December (Okumura and Xie 2006). Note that, due to the substantial reduction in JJA, peak variability in ssp585 is found in April, where the difference with piControl is negligible. Variability in the NTA is most pronounced during February and March in the observations, and this is relatively well reproduced by both piControl and ssp585, even though the amplitude is somewhat weak.

ssp585 2071-2100 - piControl: sdev of SST and U10; CMIP6 ens

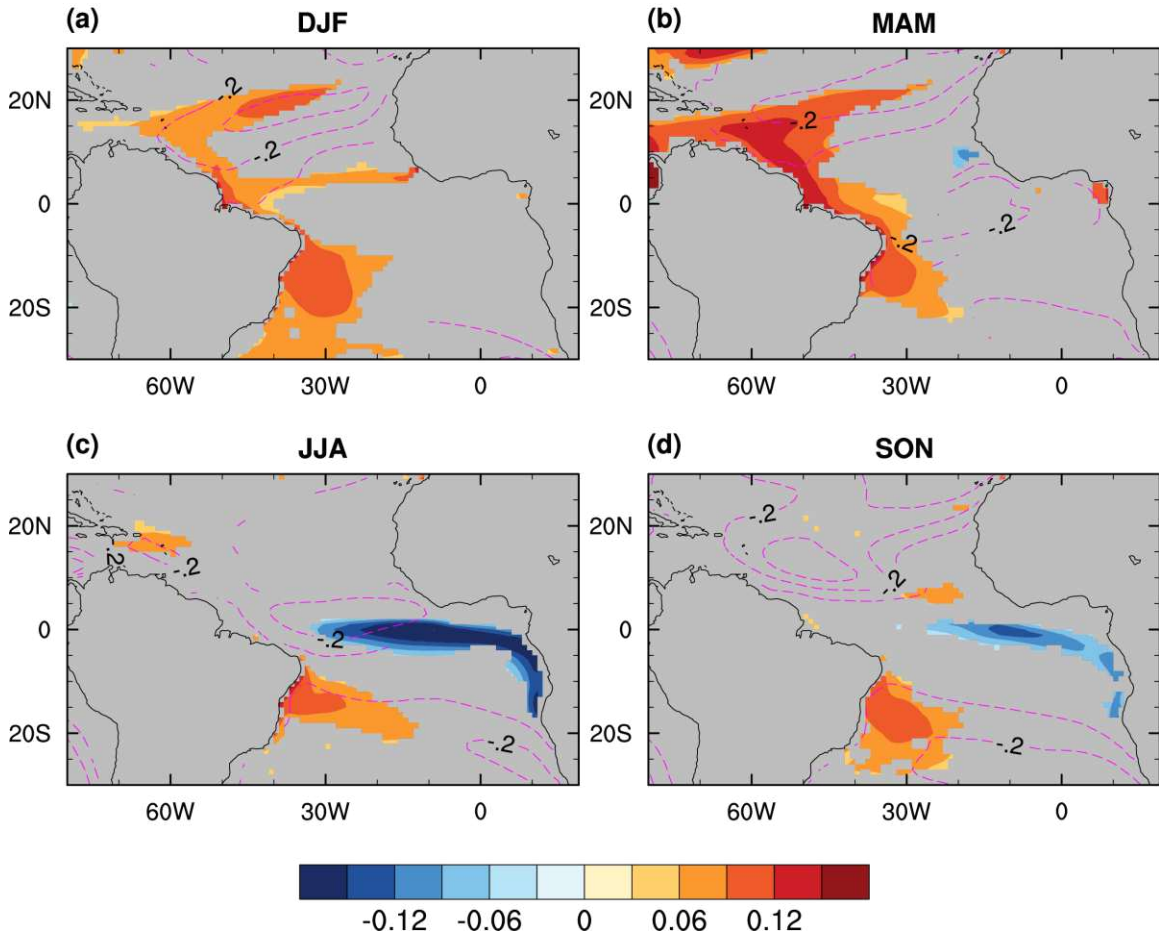


Figure 3. Similar to Fig. 1 but for the standard deviation of SST (shading; K) and 10 m zonal wind (contours; interval 0.1 m/s; negative contours dashed; zero-contour omitted). Values that do not pass the significance and robustness criteria are masked out. See section 2.3 for details on the statistical testing.

There are almost no changes from piControl to ssp585 throughout the seasonal cycle (Fig. 4b), which is due to variability decreases off West Africa being compensated by increases in the basin interior (Fig. 3). The Benguela Niño variability peaks in April. In ssp585 and piControl, this peak is delayed by one and two months, respectively, but the amplitude is fairly realistic. There is a slight decrease in ssp585 relative to piControl, particularly in the second half of the year, but none of the changes are statistically significant at the 95%

confidence level, as indicated by the overlapping confidence intervals in Fig. 4c. Both observed and simulated variability in the STA show little seasonal dependence. Relative to piControl, ssp585 features a slight increase in the beginning of the year but this change is, again, not statistically significant (Fig. 4d).

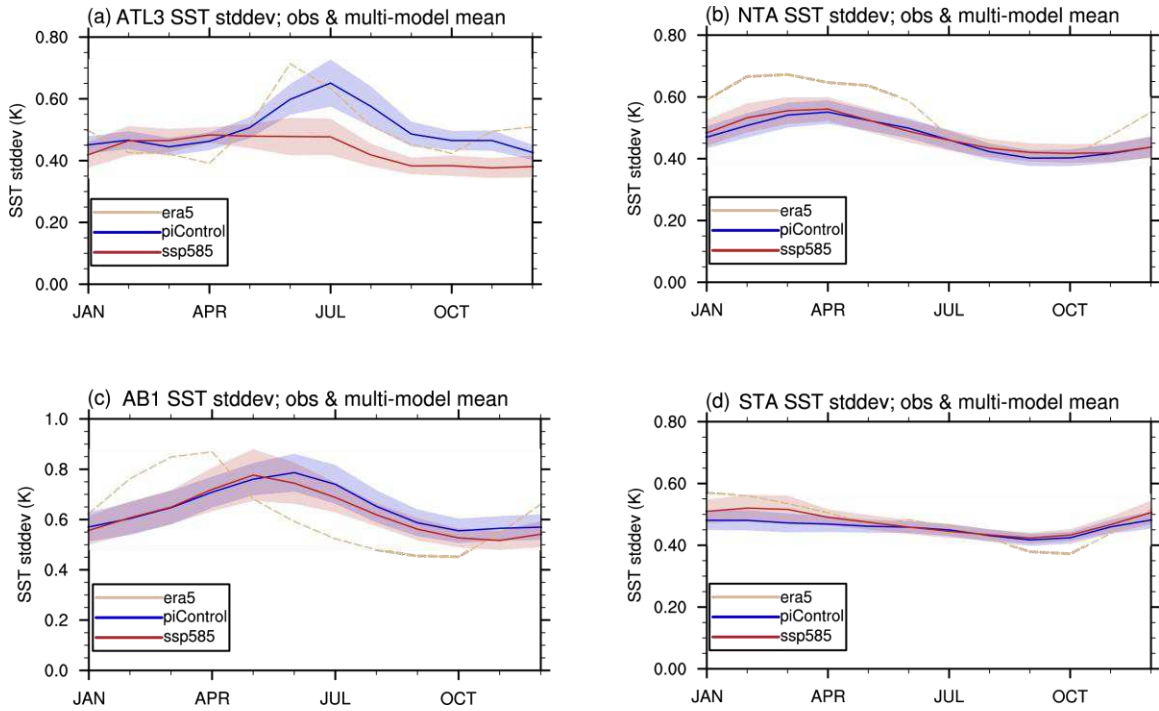


Figure 4. Standard deviation of SST for the ERA5 (beige dashed line), multi-model ensemble mean of piControl (blue line) and ssp585 (red line) for the following area averages: (a) ATL3, (b) NTA, (c) AB1, and (d) STA. The light blue and light red shading show the 95% confidence intervals for piControl and ssp585, respectively.

3.3. Equatorial Atlantic

Here, we take a closer look at how the characteristics of the AZM change in ssp585. In piControl, the ensemble mean composite of positive AZM events depicts the familiar evolution, with westerly winds in late spring and early summer preceding the ATL3 SST peak in July (Fig. 5a). Note that, in the models, the peak of the AZM event occurs one month later than in observations, which has been a consistent feature through CMIP

generations (e.g., Richter et al. 2014; Richter and Tokinaga 2020). During the whole life cycle of the AZM event, the Niño 3.4 index stays close to neutral, which is in line with the inconsistent influence of ENSO on the AZM seen in observations (Chang et al. 2006; Lübbecke and McPhaden 2012) and in many models (Richter et al. 2025). The surface net energy flux in the ATL3 is almost a perfect mirror image of the SST evolution, indicating that it acts to damp them. In other words, the thermodynamic processes are a passive response to the dynamically driven SST evolution.

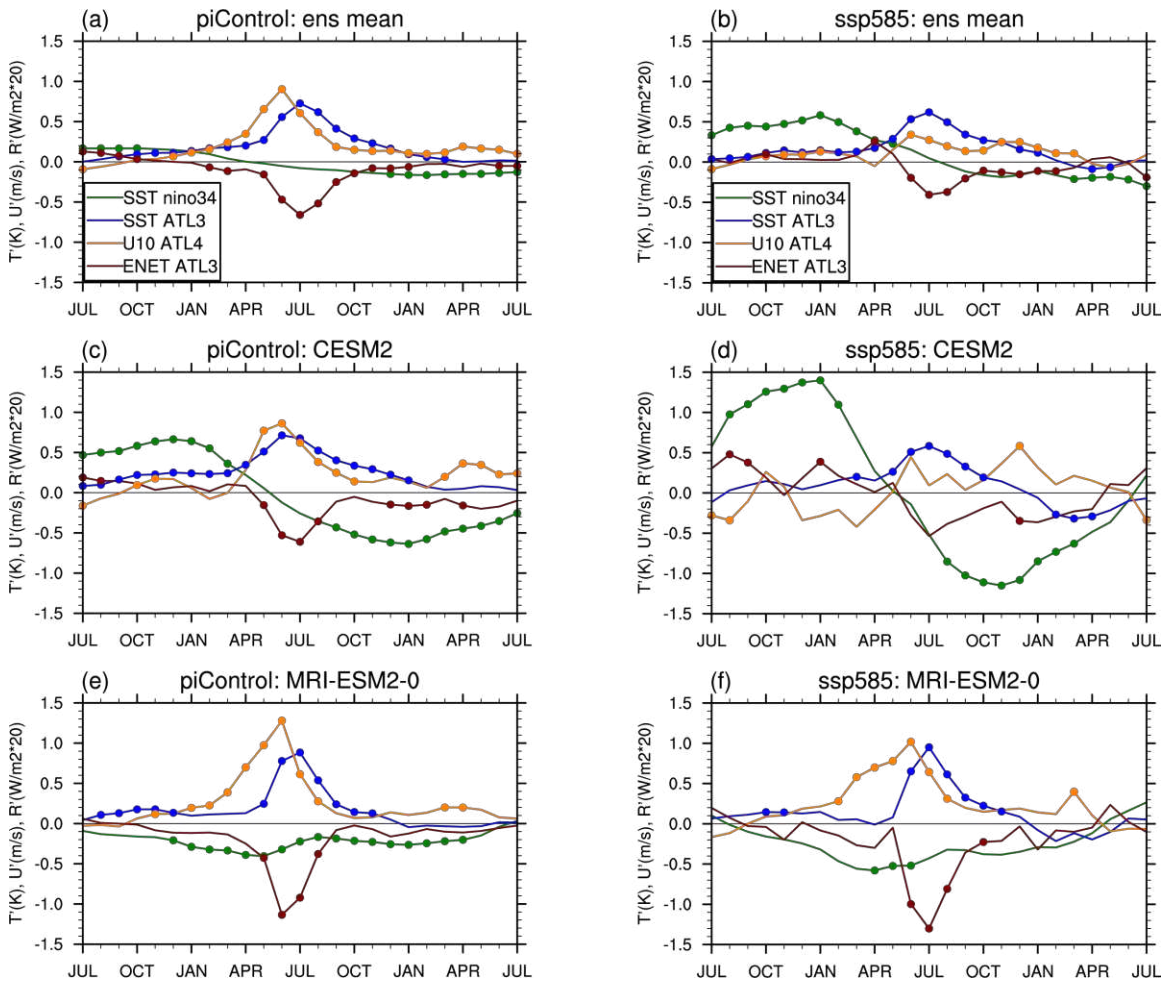


Figure 5. Composite positive AZM events, based on SST anomalies in the ATL3 region during JJA exceeding 1 standard deviation. The fields shown are Niño 3.4 SST anomalies (green), ATL3 SST anomalies (blue), ATL4 10 m zonal wind anomalies (orange), and ATL3 surface net energy flux (brown; positive means

downward flux). Filled circles mark values that are significant at the 95% confidence level. The individual panels show the (a) piControl multi-model mean, (b) ssp585 multi-model mean, (c) piControl CESM2 simulation, (d) ssp585 CESM2 simulation, (e) piControl MRI-ESM2-0 simulation, and (f) ssp585 MRI-ESM2-0 simulation.

In the ensemble mean of ssp585 (Fig. 5b), SST anomalies in the ATL3 are somewhat weaker than in piControl (Fig. 5a), consistent with previous analyses (Crespo et al. 2022; Yang et al. 2022). More striking is the absence of equatorial Atlantic wind anomalies in the developing phase: where piControl shows a slow ramping up of wind anomalies from the beginning of the year, ssp585 features neutral winds until April and weak development thereafter, with the peak being about three times weaker than in piControl. These differences between the piControl and ssp585 multi-model means are generally significant at the 95% confidence level (Fig. S3). The weak equatorial wind anomalies suggest that the role of dynamically driven processes is greatly diminished in ssp585, which is supported by the substantially reduced subsurface temperature anomalies in the eastern equatorial Atlantic and the weakened zonal gradient of heat content (Figs. S5 and S6). Note also that the temperature anomalies in the eastern equatorial Atlantic are located below the climatological thermocline in piControl (Fig. S6a) but above it in ssp585 (Fig. S6b). In addition, the subsurface warming is much weaker in ssp585, suggesting that warming through surface fluxes plays a greater role there. Consistently, the surface net energy flux has the same sign as SSTs in the ATL3 until May, meaning that it contributes to the warming, rather than damping it. Further analysis indicates that changes in both net shortwave radiation and latent heat flux contribute to the warming (not shown). We also note that the SST anomalies are around 0.5 K in the Niño 3.4 region during the developing phase of the AZM. This

suggests stronger ENSO involvement, which has been associated with thermodynamic impacts on the equatorial Atlantic (Chang et al. 2006, Richter et al. 2025).

The response to increased greenhouse gas forcing varies substantially across models. To give an impression of this spread, we show two models that are at the opposite end of the spectrum. In CESM2 (Figs. 5c and 5d), changes are pronounced, with ssp585 featuring stronger heat fluxes into the ocean during most of the developing phase, while surface winds in the ATL4 are easterly, which should lead to intensified upwelling and cooling. The fact that a warm event develops nevertheless indicates that thermodynamic processes, and potentially remotely forced subsurface oceanic processes, must play a role. There is also a clear difference in the linkage to ENSO. Where piControl only shows Niño 3.4 anomalies of about 0.5 K (Fig. 5c), ssp585 shows a pronounced El Niño with a peak of about 1.5 K in January. Previous studies have shown that El Niño events can engender equatorial Atlantic warming through the tropospheric temperature response and thermodynamic processes in the equatorial Atlantic (Chang et al. 2006; Richter et al. 2025). The pronounced El Niño preceding the AZM event indicates that this mechanism gains importance under global warming. We note that easterly wind anomalies (Fig. 5d) should lead to increased cooling by latent heat flux, if all other factors stayed the same. The actual latent heat flux anomalies, however, are warming the ocean, which means that other factors, such as air-sea temperature difference, relative humidity, and mean wind speed (e.g. Richter and Xie 2008) must have changed. More detailed analysis will be needed to determine the relative contributions to latent heat flux changes.

Another model, MRI-ESM2-0, shows little change in the AZM characteristics under global warming. The winds in the ATL4 region in ssp585 (Fig. 5f) precede the SST

warming in the ATL3 in much the same way as they do in piControl (Fig. 5e), and surface net energy fluxes oppose the SST evolution in both experiments, indicating the damping role of thermodynamic processes. The co-evolution with ENSO also remains similar from piControl to ssp585. Note that in MRI-ESM2-0 the AZM is preceded by negative SST anomalies in the Niño 3.4, as opposed to positive anomalies in CESM2, illustrating the disparate interbasin linkages across models (Richter et al. 2025).

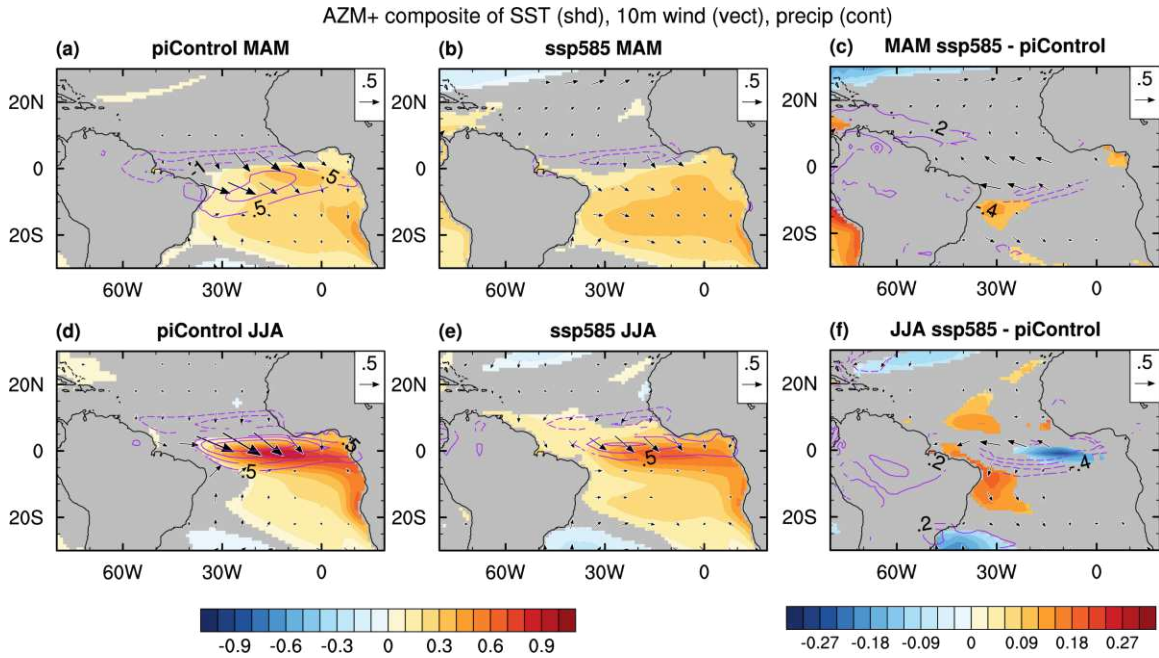


Figure 6. Composite positive AZM events, based on SST anomalies in the ATL3 region in JJA exceeding 1 standard deviation. The horizontal maps show anomalies of SST (shading; K), 10 m winds (vectors; reference vector 0.5 m/s), and precipitation (contours; contour interval 0.5 mm/day in the left two columns and 0.2 mm/d in the right column; negative contours dashed; zero-contour omitted) for (a) piControl in MAM, (b) ssp585 in MAM, (c) the difference ssp585 minus piControl in MAM, (d) piControl in JJA, (e) ssp585 in JJA, and (f) the difference ssp585 minus piControl in JJA. Values that are not significant at the 95% confidence level are masked out.

Horizontal maps of composite AZM events in piControl and ssp585 (Figs. 6 and S4) confirm the reduced role of surface wind anomalies in driving the events. They also show the southward shift of the ITCZ that accompanies AZM events, and how this response becomes much weaker in ssp585. In addition, there are changes in the AZM SST pattern. In piControl, it is narrowly confined along the equator and the coast of southwest Africa, while in ssp585 warm anomalies are more spread out, covering much of the southern tropical Atlantic and part of the northern tropical Atlantic. This again points to the strengthened influence of surface heat fluxes, which, unlike the Bjerknes feedback, are not confined to the equator.

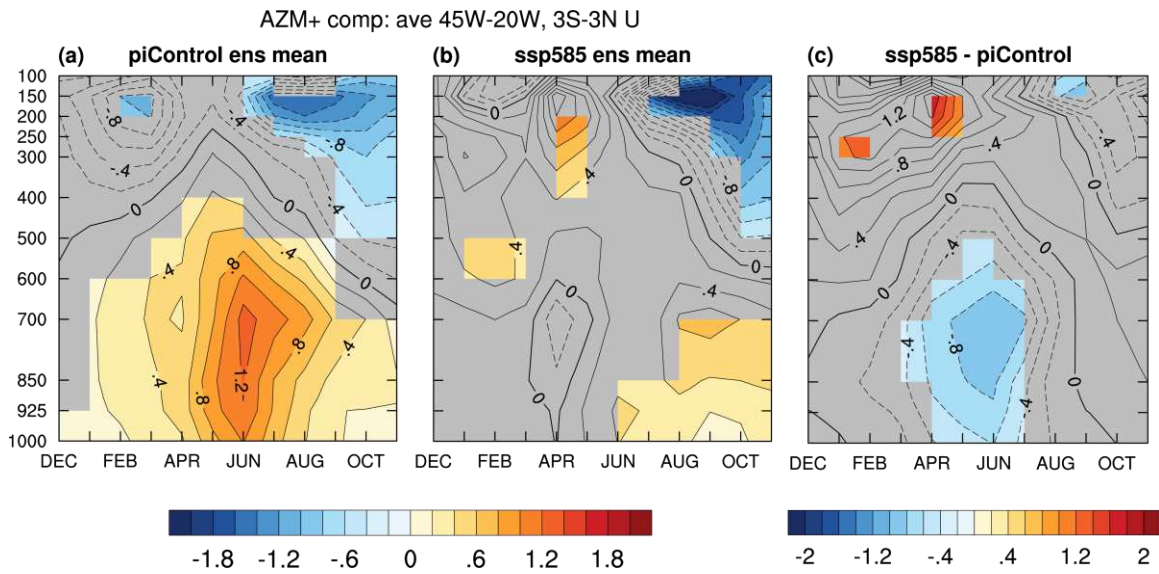


Figure 7. Pressure-time sections of zonal wind averaged in the ATL4 region for composite positive AZM events in (a) piControl, (b) ssp585, and (c) the difference ssp585 minus piControl. The compositing criterion is based on SST anomalies in the ATL3 region in JJA exceeding 1 standard deviation. Values that are not significant at the 95% confidence level are only shown in contours, significant values are also shaded.

The changing character of the equatorial wind anomalies under global warming comes into stark relief when analyzing composite pressure-time sections of zonal wind along the

equator (Fig. 7). In piControl, there is a gradual build-up of westerly wind anomalies from December through June, with a maximum in the lower troposphere. In ssp585, on the other hand, this evolution is completely absent, with wind anomalies being even slightly negative during April. In May and June, there are weak westerly anomalies, but these are most pronounced at the surface, unlike the deep structure seen in piControl. These differences again highlight that the role of dynamic wind forcing is diminished in ssp585. They also illustrate the lack of atmospheric response to SST anomalies that are only about 20% weaker in ssp585 than in piControl (Figs. 3 and 5).

3.4. On the observed decline in equatorial Atlantic variability during recent decades

Equatorial Atlantic variability has been observed to weaken from about the 1970s onward (Tokinaga and Xie 2011) with a particularly pronounced decline in the 2000s and 2010s (Prigent et al. 2020a; Worou et al. 2020). This decline may seem consistent with the results from CMIP6 projections (Crespo et al. 2022; Yang et al. 2022) and thus indicate that the impact of changing greenhouse gas concentrations on AZM variability is already observable. Here, we briefly comment on this matter.

Based on the HadISST observations, the 21-year running standard deviation of the JJA ATL3 SST peaked at 0.65 K during the period centered on 1968 (Fig. 7). The lowest variability was 0.33 K and occurred in the period centered on 2010, indicating a decrease of 0.32 K. As a rough estimate of the overall change in greenhouse gas forcing that occurred during this period, we evaluate the 21-year running mean of global surface air temperature (SAT) at those two years, which yields an increase of 0.70 K. In comparison, ATL3 variability decreases by 0.14 K (0.59 K to 0.45 K; Fig. 3a) between piControl and ssp585 (year 2071-2100), while SAT increases by 4.89 K. This would suggest that the influence of

greenhouse gas forcing on AZM variability is about 16 times stronger in observations than in the CMIP6 models. Consistently, the multi-model mean of historical and ssp585 simulations show only a slight decrease in variability over the period 1968-2010 (Fig. 8a). Thus it is highly likely that the recent observed decline in AZM variability is mostly related to other causes, such as internal multi-decadal variability associated with the Atlantic Meridional Overturning Circulation (AMOC; Freire-Souza et al. 2025; Vilela et al. 2025), or errors in the aerosol forcing applied in CMIP6 historical experiments. This is also supported by the recent uptick in AZM variability as observed in late 2019 (Richter et al. 2022), in 2021 (Lee et al. 2023), and in 2024 (Tuchen et al. 2025). Alternatively, the models fail to properly represent the effect of greenhouse gas forcing on equatorial Atlantic variability due to systematic errors.

The envelope in Fig. 8a indicates that the intermodel spread is large and fully covers the observed range. This, however, does not mean that any given model can reproduce the observed range. To examine this, we check whether the piControl simulations can produce variability changes that are equal to or greater than the observed change during the 43-year period from 1968 to 2010 (Fig. 8b). The histogram of all 43-year periods from all models shows that the observed change lies outside the 95th percentile range but still just inside the 99th percentile. Interestingly, a similar analysis for the increase in NDJ ATL3 SST variability during the 50-year period 1921-1970 (Fig. 8a, c) suggests that its change lies outside the 99th percentile range. However, because this change occurred before the satellite observation era, it is subject to considerable uncertainty.

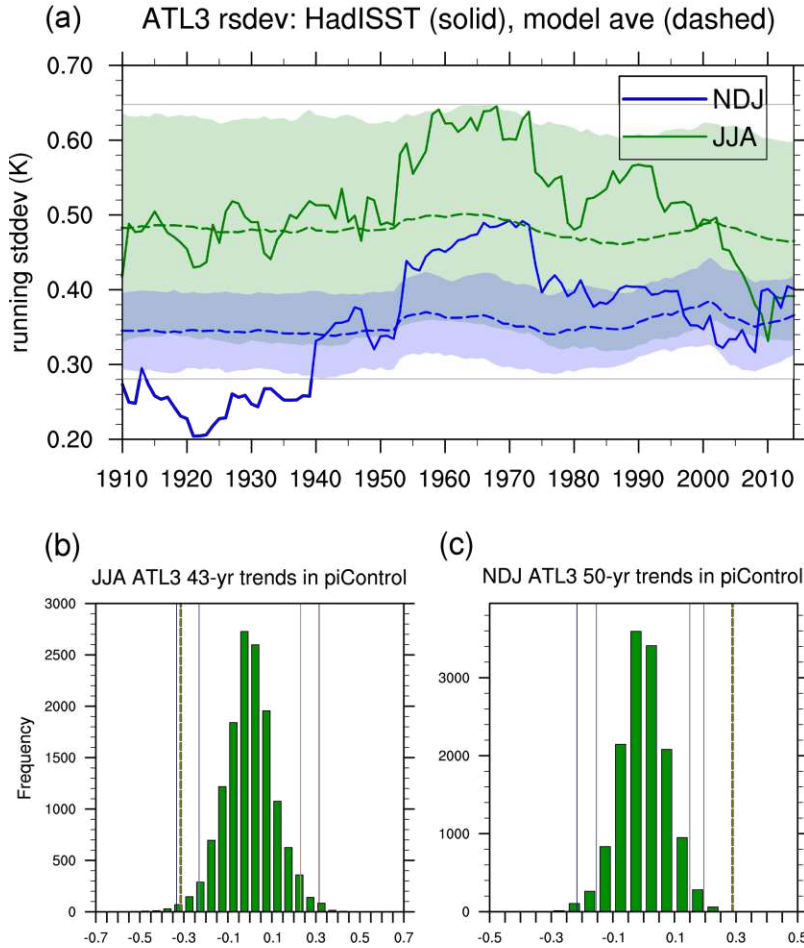


Figure 8. (a) Running standard deviation of ATL3 SST averaged over JJA (green line) and NDJ (blue line). A 21-year window is moved with the value for a given year corresponding to the center point of the window (e.g., the value at 1980 is the standard deviation calculated from 1970-1990). The data is from the HadISST. The dashed lines show the multi-model mean running standard deviations of the concatenated historical and ssp585 simulations spanning the same period, with the green and blue shading indicating the standard deviation across the model dimension for JJA and NDJ, respectively. (b) Histogram showing the distribution of 43-year trends in the 21-year running standard deviation of JJA ATL3 SST in piControl. Each 43-year period in each model contributes one data point. The light blue and pink lines show the 95th percentile, the dark blue and red line the 99th percentile. The dashed line shows the most pronounced change in the HadISST observations, which occurred during the 43-year period from 1968 to 2010. (c) Similar to (b), but for 50-year trends of the NDJ ATL3 SST, with the dashed line showing the extreme change that occurred during the period 1921 to 1970.

3.5. Northern tropical Atlantic

Composites of positive AMM events piControl (Fig. 9a), defined by SST warming in the NTA region during MAM, show that the surface net energy flux acts to warm the ocean from around November of the preceding year, leading to the gradual warming of NTA SST anomalies, which peaks in April. The anomalous heat flux into the ocean is mostly due to the reduction of local surface wind speed (Fig. 9a), which reduces latent heat flux (not shown) and may be associated with the WES feedback. It is also apparent that the AMM event is preceded by weak El Niño conditions in the Pacific, which is consistent with the well-known influence of ENSO on the northern tropical Atlantic (Enfield and Mayer 1997). The most significant change in ssp585 is the strengthening of the preceding El Niño event (Fig. 9b), which is significant at the 95% confidence level (Fig. S9a). The other fields remain quite similar. CanESM5 is an example of a model with weak ENSO linkage (Fig. 9c), as Niño 3.4 SSTs remain close to neutral during the entire AMM event. This linkage slightly strengthens in ssp585 (Fig. 9d). EC-Earth3, on the other hand, represents a model in which the ENSO influence becomes dominant in ssp585 (Figs. 9e and 9f). The preceding El Niño is much more pronounced in ssp585, and this is accompanied by a more pronounced weakening of the surface winds and increased warming by the net surface energy flux. As a result, the amplitude of the AMM event also increases.

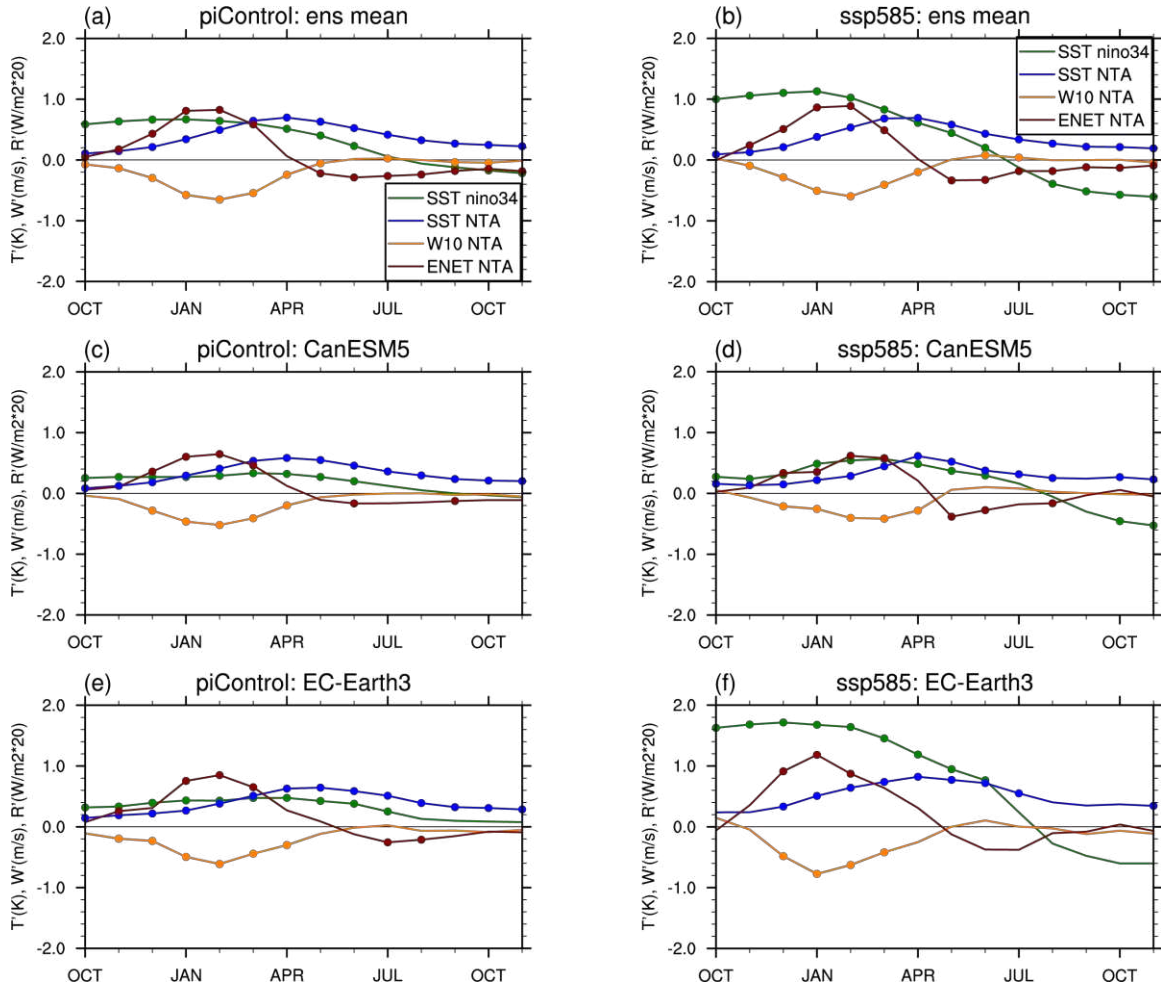


Figure 9. Composite positive AMM events, based on SST anomalies in the NTA region during MAM exceeding 1 standard deviation. The fields shown are Niño 3.4 SST anomalies (green), NTA SST anomalies (blue), NTA 10 m wind speed anomalies (orange), and NTA surface net energy flux (brown; positive means downward flux). Filled circles mark values that are significant at the 95% level. The individual panels show the (a) piControl multi-model mean, (b) ssp585 multi-model mean, (c) piControl CanESM5 simulation, (d) ssp585 CanESM5 simulation, (e) piControl EC-Earth3 simulation, and (f) ssp585 EC-Earth3 simulation.

3.6. Southern tropical Atlantic

Like its northern counterpart, the southern tropical Atlantic is mostly characterized by an increase in SST variability under global warming (Fig. 3). The most pronounced SST

variability pattern in the region, however, is the Benguela Niño, which is thought to mostly rely on dynamical processes. Consistent with the decreased standard deviation of SST in JJA and SON (Fig. 3), composite Benguela Niño events weaken under increased greenhouse gas forcing (Figs. 10a and 10b). In piControl (Fig 10a), events are preceded by westerly wind anomalies over the equatorial Atlantic, which indicates the dynamical influence of downwelling Kelvin waves that propagate to the region along the equatorial-coastal waveguide. A weakening of the along-shore wind anomalies is also in evidence, albeit not very pronounced. ENSO anomalies are weak, and the net surface energy flux damps the SST anomalies throughout the lifecycle of the event. The most striking difference in ssp585 (Fig. 10b) is the pronounced weakening of equatorial wind anomalies, which is significant at the 95% confidence level (Fig. S10a). The changes in net surface energy flux are more subtle but suggest a more active role in the evolution of the event, as the fluxes are slightly positive or less negative during the developing phase. The piControl composite of EC-Earth3 (Fig. 10c) is quite similar to the multi-model ensemble mean (Fig. 10a) but changes markedly in ssp585 (Fig. 10d), with more pronounced westerly and northerly anomalies during the developing phase in the ATL4 and AB2 regions, respectively, a La Niña preceding the event, and thermodynamic processes gaining an active role in the development. The resulting composite event retains almost the same peak strength as in piControl. In HadGEM3-GC31-MM, on the other hand, there is a drastic decrease in equatorial zonal wind anomalies (Figs. 10e and 10f), and the event weakens substantially.

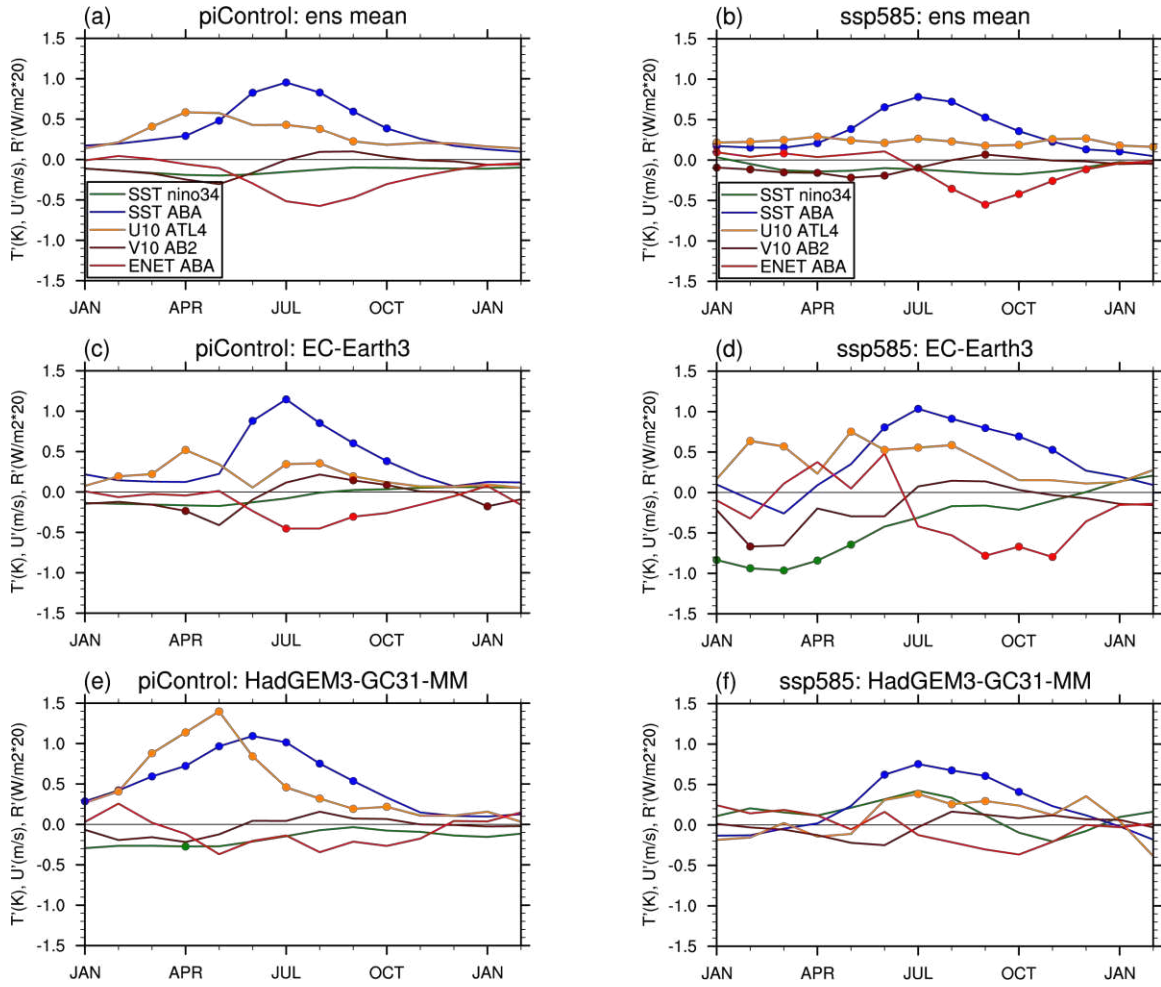


Figure 10. Composite Benguela Niño event, based on SST anomalies in the ABA region during JJA exceeding 1 standard deviation. The fields shown are Niño 3.4 SST anomalies (green), ABA SST anomalies (blue), ATL4 10 m zonal wind anomalies (orange), AB2 10 m meridional wind anomalies (brown), and ABA surface net energy flux (red; positive means downward flux). Filled circles mark values that are significant at the 95% confidence level. The individual panels show the (a) piControl multi-model mean, (b) ssp585 multi-model mean, (c) piControl EC-Earth3 simulation, (d) ssp585 EC-Earth3 simulation, (e) piControl HadGEM3-GC31-MM simulation, and (f) ssp585 HadGEM3-GC31-MM simulation.

4. Changing remote linkages

In section 3, we saw that both AZM (Fig. 5) and AMM (Fig. 9) events show a stronger ENSO signal in ssp585 than in piControl. While ENSO amplitude increases by about 20%

in ssp585 (not shown) this cannot explain the 2-3 times stronger ENSO signal in the composites. The ssp585 composites therefore suggest a strengthening influence of ENSO on the equatorial and northern tropical Atlantic. We examine this further using lagged correlation analysis (Fig. 11). The correlations are calculated for each ensemble member of each model, then averaged for each model using the z-transformation and finally averaged over all models, again using the z-transformation. For piControl, there is only one ensemble member, so the first averaging step is not needed.

The lagged correlations of the DJF Niño 3.4 index with the ATL3 index (Figs. 11a, b) and NTA index (Figs. 11c, d) confirm a stronger association of ENSO with AZM and AMM events. It is interesting to note, however, that the correlation of the DJF Niño 3.4 with the ATL3 is highest at lag 3 months (piControl; April) or lag 2 months (ssp585; March), which is the early developing phase of the AZM. It should also be noted that the positive correlation in both piControl (0.45) and ssp585 (0.70) is more pronounced than what is seen in observations, where it peaks in February at about +0.2 (Richter et al. 2024). The correlation of the DJF Niño 3.4 with the ATL4 is negative at all lags in both piControl and ssp585, which means that El Niño events are associated with easterly wind anomalies over the equatorial Atlantic, consistent with observations (Richter et al. 2025). Easterly wind anomalies should induce cooling in the equatorial Atlantic as they strengthen both upwelling and latent heat flux. The fact that the ATL3 SST is positively correlated with Niño 3.4 SST therefore suggests a strengthening influence of ENSO's thermodynamic forcing. This is supported by the positive correlation of the surface net energy flux. This correlation is more pronounced in ssp585 than in piControl, again indicating a strengthening influence of thermodynamic processes under greenhouse gas forcing.

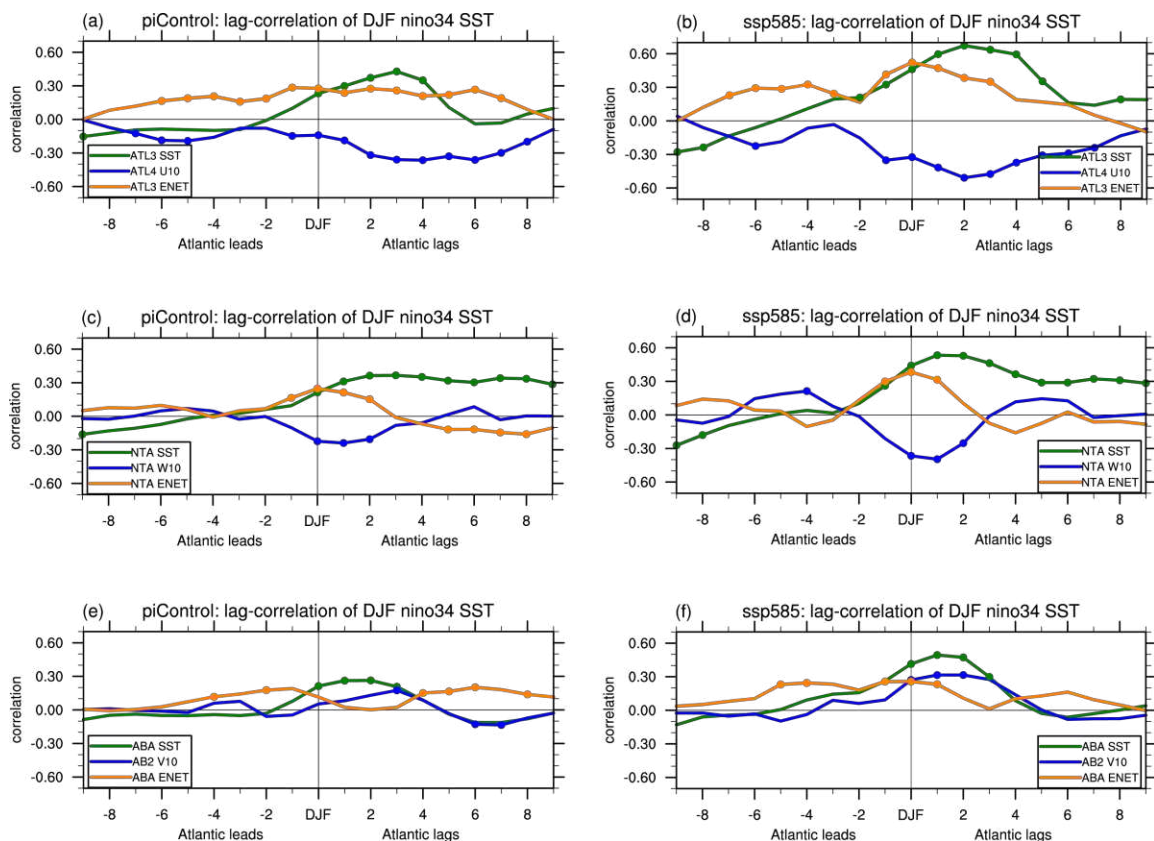


Figure 11. Lead-lag correlation of the DJF Niño 3.4 index with (a,b) ATL3 SST (green line), ATL4 10 m zonal wind (blue line), and ATL3 net surface energy flux (orange line); (c,d) NTA SST (green line), NTA 10 m wind speed (blue line), NTA net surface energy flux (orange line); (e,f) ABA SST (green line), AB2 10 m meridional wind (blue line), and ABA net surface energy flux (orange line). The left column shows piControl, the right column shows ssp585. Ensemble averages of the correlations are calculated using the z transformation. Filled circles indicate values that are significant at the 95% level.

At longer lags, the ATL3 correlation with ENSO weakens. At lag 6 months, during the peak season of the AZM, it is 0.0 in piControl and 0.2 in ssp585. This is consistent with the observed inconsistent influence of ENSO on the AZM (Chang et al. 2006; Lübbecke and McPhaden 2012; Richter et al. 2025). While the thermodynamic forcing associated with ENSO becomes stronger in ssp585, this only leads to a slightly stronger association with the AZM in the ensemble mean.

Positive AZM events in the presence of easterly wind anomalies have also been explained through the delayed impact of off-equatorial Rossby waves (Lübbecke and McPhaden) and meridional advection of subsurface ocean temperatures (Richter et al. 2013). Composite longitude-time sections of heat content north of the equator show some evidence for off-equatorial Rossby waves in ssp585 (Fig. S11c) but the reflection at the western boundary is weak and not statistically significant (Figs. S11d and S12d). Meanwhile, subsurface warming between 3°N and 5°N during positive AZM events becomes more pronounced (Fig. S7) suggesting a possible role of the meridional advection mechanism. Both effects appear to be relatively weak but more thorough analysis would be required to confirm this.

The peak correlation of the Niño 3.4 index with the NTA SST index increases from 0.35 in piControl (lag 2 months; Fig. 11c) to 0.55 in ssp585 (lag 1 month; Fig. 11d). The lags with high correlation include the MAM peak season of the AMM, suggesting that the ENSO's association with the AMM strengthens. The role of the net surface energy flux is evident by the stronger positive correlations with a peak at lag 0 months (about 0.2 in piControl vs. 0.4 in ssp585). The correlation with surface wind speed in the NTA is almost opposite to that with the net surface energy flux, which indicates that the flux changes are mostly due to ENSO's influence on surface winds in the NTA region.

The correlation with the ABA SST index increases from about 0.3 in piControl (lag 1 month; Fig. 11e) to 0.5 in ssp585 (lag 1 month; Fig11f), suggesting a stronger association of ENSO with the Benguela Niño under global warming, including during its peak season in MAM. This appears to be due to the net surface energy flux playing a stronger role in ssp585 at lags 0 through 2 months.

Previous studies have suggested that ENSO can be influenced by both the AZM (Rodríguez-Fonseca et al. 2009) and the AMM (Ham et al. 2013). While the influence of the Atlantic on ENSO is not the focus of this study, we briefly note that, in the ensemble mean, the models do not suggest a strong influence of the Atlantic on ENSO (negative lags in Figs. 11a-11d), which is true for both piControl and ssp585.

The changing role of ENSO on the AZM is further illustrated by longitude-pressure sections along the equator for composite AZM+ events during AMJ (Figs. 12 and S8). In piControl (Figs. 12a and S8a), anomalies of pressure velocity (ω ; note that positive indicates sinking motion) are neatly confined to the Atlantic sector, with anomalous rising motion in the east and sinking motion in the west. The developing warming in the eastern equatorial Atlantic is evident in the positive temperature anomalies in the lower troposphere. There are also warm anomalies in the upper troposphere, which result from the latent heat release associated with deep convection. These upper warming anomalies are spread across the globe, consistent with the tropospheric temperature mechanism (Yulaeva and Wallace 1994; Chiang and Sobel 2002; Chiang and Lintner 2005). These remote temperature anomalies, however, are weak, typically not exceeding 0.15 K.

The same composite for ssp585 shows drastically different patterns (Figs. 12b and S8b). The ascending branch over the eastern equatorial Atlantic has disappeared, indicating the absence of a convective response. Instead, there is ascending motion over the equatorial Pacific with a peak around 120°W, associated with near-surface warming that is indicative of El Niño conditions. Inspection of the associated SST patterns in the tropical Pacific (not shown) confirms that, in ssp585, the positive AZM is associated with warm SST anomalies that persist from the DJF peak into AMJ.

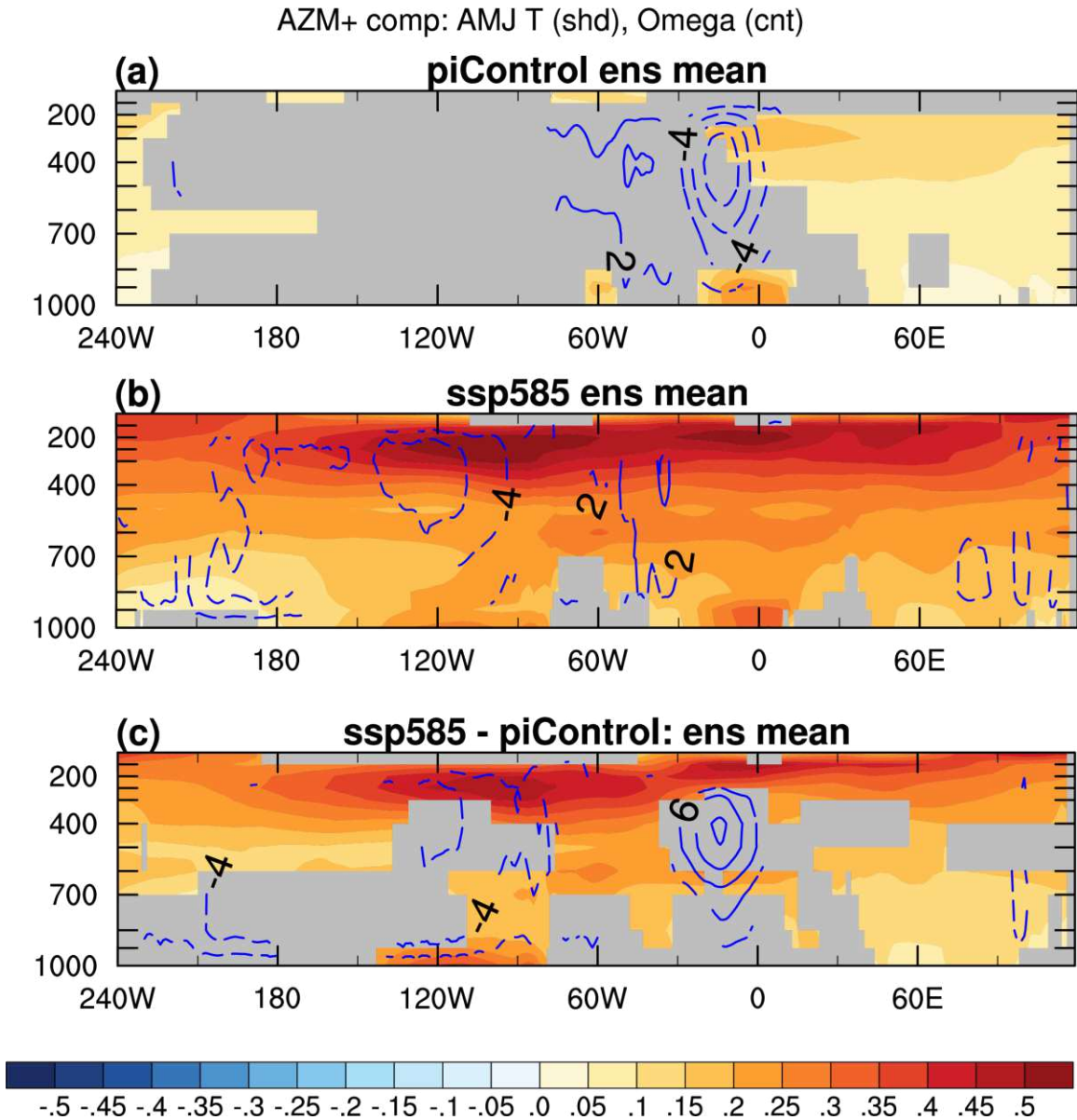


Figure 12. Longitude-pressure sections of atmospheric temperature (shading; K) and vertical pressure velocity (contours; interval 2 hPa/day; negative values dashed; zero-contour omitted) in AMJ, averaged between 5S to 5N, for the multi-model ensemble mean of (a) piControl, and (b) ssp585.

Aloft, in the upper troposphere, there is warming exceeding 0.5 K that is associated with latent heat release. Due to the tropospheric temperature mechanism, the upper tropospheric warming spreads to all longitudes and is pronounced over the equatorial Atlantic,

where its stabilizing effect explains the absence of a convective response to the AZM event. The descending motion over the western equatorial Atlantic likely results from an eastward shift in the Pacific Walker circulation. These results indicate that ENSO exerts stronger control on the AZM in a warmer climate, potentially suppressing variability that arises from ocean-atmosphere interactions within the tropical Atlantic.

5. Changes in predictability

To assess changes in the predictability of the AZM, we use the multiple linear regression model presented in Richter et al. (2025). This simple model relies on five SST-based indices, namely Niño 3.4, Niño 3.4 tendency, NTA, STA, and ATL3. These five predictors are used to predict the JJA ATL3 from DJF. For a justification of the predictors please refer to Richter et al. (2025). For the ssp585 experiment, the 2071-2100 time periods of each ensemble member of a given model are concatenated to create one continuous time series. To avoid problems with the discontinuity at 30-year intervals, we discard the predictions for these years.

We first examine the relative importance of predictors. This is estimated based on the entire time series available for each model. All five predictors are fitted to the predictand, and the predictor with the highest correlation skill is chosen as the dominant predictor and its contribution is regressed out. Then the four remaining predictors are fitted to the residual variability to determine the second predictor. This procedure is repeated until all predictors have been ranked

In piControl, the most important predictor in most models is the STA index (Fig. 13a). This is consistent with the results of Richter et al. (2025). There are only two models in which the Niño 3.4 index emerges as the dominant predictor: FGOALS-g3 and GISS-E2-

1-H. In several other models, the Niño 3.4 index also plays an important role as the second predictor. The other predictors usually play only a small role.

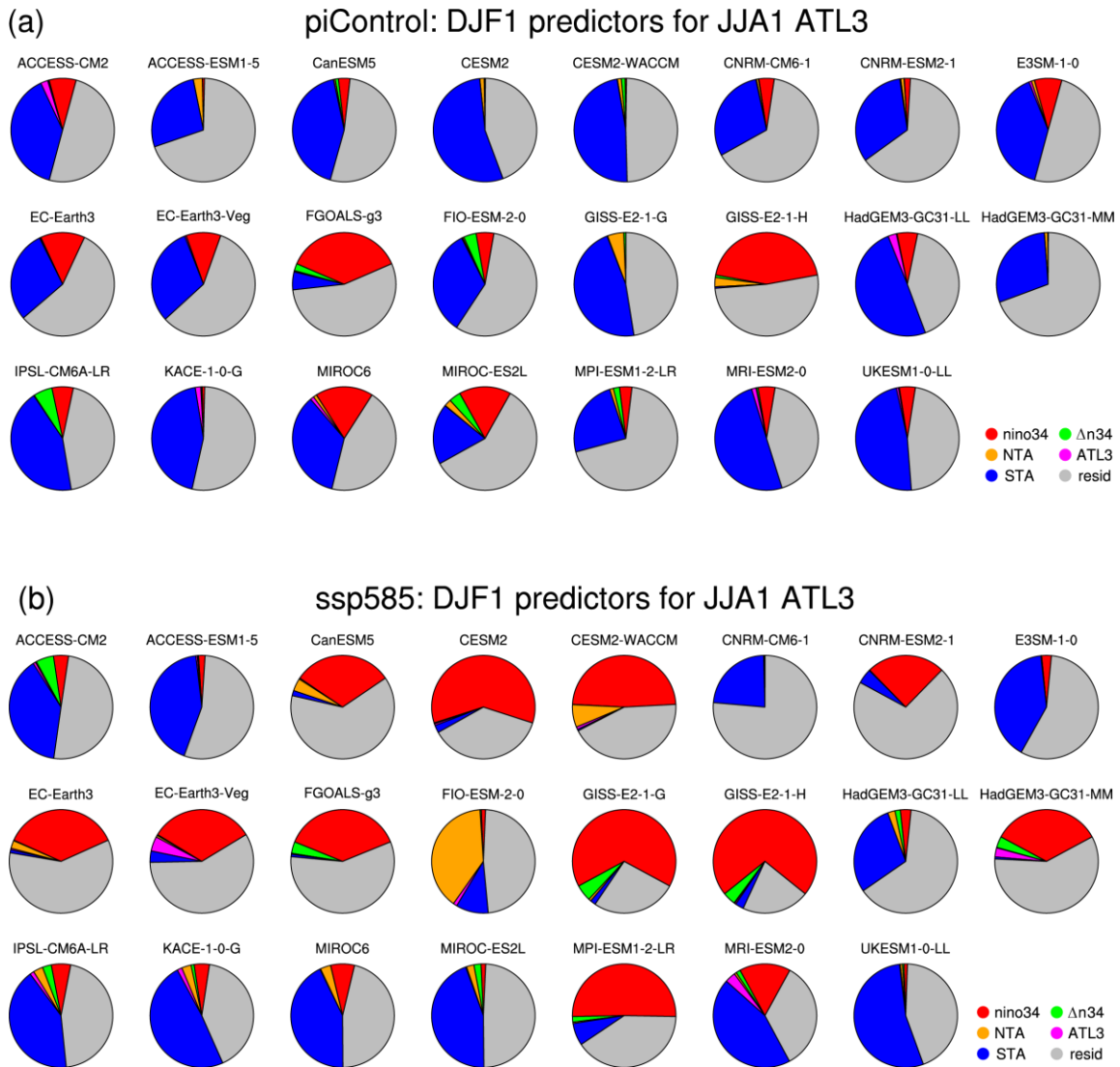


Figure 13. Predictor analysis for individual models in (a) piControl, and (b) ssp585. The largest segment of each pie chart shows the anomaly correlation coefficient (ACC) of the dominant predictor, while the smaller segments show the gain in ACC obtained by adding the indicated predictor. The colors denote Niño 3.4 SST (red), NTA SST (orange), STA SST (blue), Niño 3.4 SST tendency (green), ATL3 SST (magenta), and the residual (grey).

Under the ssp585 forcing, many models show a shift toward the Niño 3.4 index as the dominant predictor, with other predictors only making minor contributions (Fig. 13b). Some striking examples are CanESM5, CESM2, GISS-2E-1-G, HadGEM3-GC31-MM, and MPI-ESM1-2-LR. The shift toward ENSO domination in CESM2 is consistent with the changes seen in the AZM composites (Figs. 5c and 5d). Likewise, the moderate increase of Niño 3.4 importance in MRI-ESM2-0 is consistent with the stability of its AZM composite (Figs. 5e and 5f). The increased importance of the Niño 3.4 index as a predictor is not related to the generally increased ENSO amplitude in ssp585. In fact, some of the models with the highest increase in the ENSO correlation coefficient, such as the CESM2, display little change in the Niño 3.4 SST standard deviation during the DJF peak (not shown).

We next examine prediction skill by using the first half of each model's time series as the training period and the second half as the test period and again predicting the JJA ATL3 from the preceding DJF. Changes in prediction skill are inconsistent, with about half the models showing an increase in ssp585, while the other half shows a decrease (Fig. 14). The GISS-E2-1-G and MPI-ESM2-1-LR represent models where the shift to an ENSO-driven AZM results in higher predictability, as could be expected from the generally high predictability associated with ENSO. This, however, is not always the case, as exemplified by the CNRM-ESM2-1, where the stronger ENSO influence is associated with a drop in AZM skill. Other examples are the CanESM5 and HadGEM3-GC31-LL, which featured relatively realistic AZM dynamics in piControl, with ATL4 wind anomalies preceding the peak in ATL3 SST (Fig. 15) and the net surface energy flux playing a passive role (not shown for individual models but similar to what is seen for the ensemble mean in Fig. 5a). A diminished role of ATL4 wind stress forcing is seen in most models (Fig. 15) and is

719 consistent with the decreased predictability in many models. A predictability increase tends
720 to occur in models where the ENSO influence is stronger than observed under present con-
721 ditions (not shown). In such models, the ENSO influence in ssp585 becomes strong enough
722 to take over the role of local dynamics.

723 We also take a brief look at predictability changes of the AMM and Benguela Niño.
724 For the AMM, we predict the MAM NTA SST index at a lead of two seasons using as
725 predictors the Niño 3.4 index, the ATL3 index, the NTA SST index itself, the NTA wind
726 index, and the STA index. While the Niño 3.4 is already the dominant predictor in piCon-
727 trol in many models, it becomes even more important in ssp585 (Fig. S13). The only ex-
728 ception is the FGOALS-g3, where the ATL3 becomes the dominant predictor. Overall, the
729 results suggest increased predictability of the AMM in ssp585.

730 For the Benguela Niño, we predict the JJA ABA SST index at a lead of one season,
731 using as predictors the Niño 3.4 index, the ABA SST index itself, the ATL4 zonal wind
732 index, the AB2 meridional wind index, and the ATL3 index (Fig. S14). In piControl, the
733 ABA index is the dominant predictors in the majority of models (13), followed by the Niño
734 3.4 index (6), the AB2 index (2), and the ATL4 and ATL3 indices (one each). In ssp585,
735 many models switch from the Niño 3.4 index to the AB2 index as the dominant predictor.
736 This suggests that local processes, specifically the along-shore wind anomalies, become
737 more important factors in the generation of Benguela Niños.

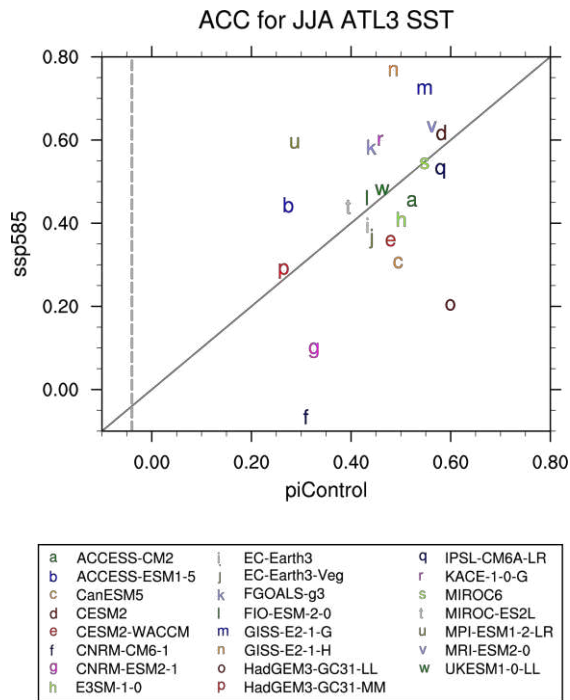


Figure 14. Prediction skill, as measured by the ACC metric, for ATL3 SST anomalies in JJA using the predictors shown in Fig. 13 two seasons earlier (DJF). Each letter represents one model, with the x and y axes indicating the skill in piControl and ssp585, respectively. The dashed vertical line shows the ACC for ERA5.

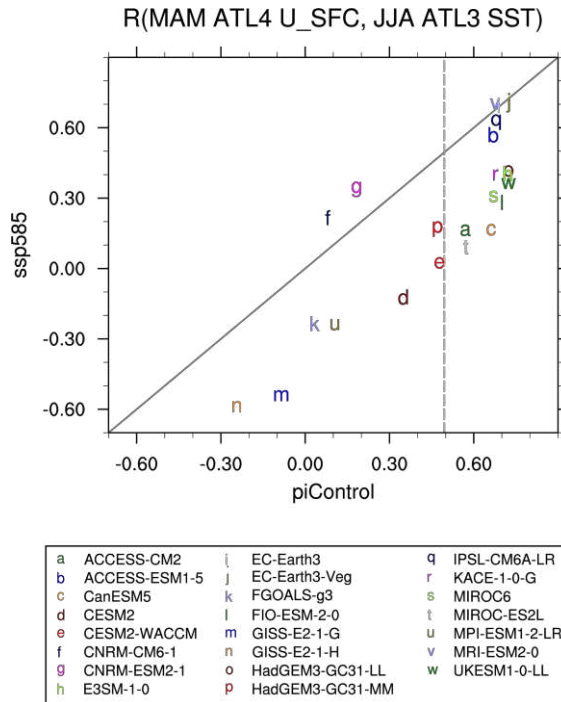


Figure 15. Correlation of MAM 10 m zonal wind in the ATL4 region with SST in the ATL3 region one season later (JJA). Each letter represents one model, with the x and y axes indicating the skill in piControl and ssp585, respectively. The dashed vertical line shows the correlation calculated from ERA5.

6. Summary and discussion

6.1. Summary

We have investigated the changes of tropical Atlantic variability projected by CMIP6 models under the high emission scenario ssp585. Consistent with previous studies, we find decreased SST variability along the equator and the southwestern coast of Africa. In most other regions of the tropical Atlantic, there is a slight to moderate increase in variability.

A detailed analysis of the AZM, the equatorial variability pattern, shows that the role of dynamic processes in the equatorial Atlantic is diminished under greenhouse gas forcing. Whereas westerly wind anomalies are an essential element in piControl, they play a secondary role in ssp585, with thermodynamic processes becoming more important. In

addition, the contribution of dynamic oceanic processes in the northern equatorial Atlantic to AZM variability may increase under radiative forcing.

Individual models show a wide range of responses to greenhouse gas forcing. In some, the AZM becomes primarily driven by thermodynamic processes, while in others, dynamic processes continue to dominate. The more prominent role of thermodynamic forcing is mostly due to the reduced trade wind variability and the weakening of the Bjerknes feedback, for which the general atmospheric stabilization plays an important role.

The influence of ENSO on the AZM strengthens under global warming. As shown by composite analysis, there is a tendency in ssp585 for AZM events to be preceded by ENSO events of the same sign. Lagged regression analysis further shows that the positive association between ENSO and the AZM is particularly pronounced in late boreal winter and early spring. As shown in previous studies (Chang et al. 2006; Richter et al. 2025), such a positive association is indicative of the thermodynamic ENSO influence through the tropospheric temperature mechanism (Chiang and Sobel 2002). The strengthened ENSO influence is evident in the vertical atmospheric temperature sections of composite positive AZM events in ssp585, which show pronounced upper tropospheric warming that is most pronounced over the eastern equatorial Pacific. This stabilizes the atmosphere over the equatorial Atlantic and inhibits deep convection despite the developing SST anomalies.

During the period 2000-2019 the AZM has weakened (Prigent et al. 2020a; Richter et al. 2022), which raises the question whether greenhouse gas increases are already affecting equatorial Atlantic variability. Our analysis suggests that this is not the case. Compared to the increase of greenhouse gas concentrations in ssp585 projections, the increase during the historical period is much too small to have a significant impact on variability.

Furthermore, the historical simulations with observed radiative forcing do not show a consistent decrease of AZM variability during the period 1900-2024. Comparison with CMIP6 piControl simulations shows that the decline is outside the 95th percentile of internal variability, suggesting that external radiative forcing played a role. While the CMIP6 historical forcing includes estimates of the radiative forcing, it is possible that this forcing does have some biases, particularly with respect to aerosol radiative forcing. Alternatively, the forcing is correct but its effect on climate variability, including the AMOC, is not adequately represented by the models.

The stronger ENSO influence in ssp585 can lead to increased AZM predictability due to ENSOs longer time scales. This, however, occurs in only about half of the models, with the other half showing a decline in predictability. This decline can only partly be explained by the reduction in AZM variability. More important seems to be the weakened air-sea coupling in the equatorial Atlantic.

ENSO's influence on the tropical Atlantic also strengthens off the equator, particularly over the northern tropical Atlantic, where stronger ENSO-induced wind speed anomalies drive stronger latent heat flux anomalies. Similar mechanisms seem to be at work in the southern tropical Atlantic. For the AMM and Benguela Niños, predictability generally increases but only in the former does the ENSO influence become more dominant.

6.2. Discussion

Previous studies have suggested that the weakening of the Bjerknes feedback is partly due to the deeper thermocline under radiative forcing. These studies, however, used the depth of the 20°C isotherm as a proxy for thermocline depth. In contrast, our results suggest that the actual thermocline shoals in the future scenario. In addition, the maximum temperature gradient increases. Such changes have been associated with increased variability in

the equatorial Pacific (Philip and van Oldenburg 2006; Yang and Zhang 2008; Collins et al. 2010). A closed heat budget analysis may be necessary to comprehensively understand how oceanic mean state changes affect the AZM.

Our results suggest that, under strong greenhouse gas forcing, tropical Atlantic variability becomes increasingly driven by thermodynamic processes. This mostly manifests in the equatorial/coastal wave guide, where dynamic processes play a dominant role under present-day conditions. While these impacts are robust in the multi-model mean, there is a wide range of responses across the CMIP6 models. It is important to understand which responses are realistic. A common approach is to assign higher credibility to the models that simulate present-day conditions more realistically, but such a ranking is not straightforward. Figure 15 provides a measure of the importance of dynamic processes in a given model, with “dynamic” models showing higher correlations on the x-axis. In the upper right of this diagram, there is a cluster of models that overestimate the importance of dynamics but also show little change in ssp585, i.e. dynamic processes continue to dominate. This group includes the IPSL-CM6A-LR and the MRI-ESM2-0, which, incidentally, were also ranked among the highest in terms of their ability to realistically simulate AZM variability by Richter and Tokinaga (2020). There is also a cluster of models that overestimate the importance of dynamics in piControl and do show a strong decline in ssp585, including MIROC6, which also ranked relatively highly in Richter and Tokinaga (2020). Meanwhile, a few models with relatively realistic dynamic impacts in piControl show a more dramatic decline under the ssp585 scenario. Among them is the CESM2, another model that ranked highly in Richter and Tokinaga (2020). The disparate global warming response of models with relatively realistic AZM variability highlights the difficulty of constructing emergent

constraints. Examining the reasons for the robustness of AZM variability in some models will be an important next step for understanding how radiative forcing affects tropical Atlantic variability.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

IR conceptualized and designed the study, performed the analysis, and wrote the original draft. All authors contributed to reviewing and editing subsequent drafts. All authors read and approved the final manuscript.

Data Availability

All the datasets used in this study are publicly available. The ERA5 and ORAS5 reanalyses can be obtained from the C3S Climate Data Store at <https://cds.climate.copernicus.eu/datasets>. HadISST data are available from <https://www.metoffice.gov.uk/hadobs/hadisst/>. The CMIP6 model datasets are available from the Earth System Grid Federation (ESGF) at <https://esgf-node.llnl.gov/search/cmip6/>.

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