



Tropical Atlantic variability in EC-EARTH: impact of the radiative forcing

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Abstract

Understanding the impact of radiative forcing on climate variability and change in the Tropical Atlantic is crucial for different socio-economic sectors, given their substantial impacts in both local and remote regions. To properly evaluate the effect of a changing climate on the variability, the use of standard transient historical and scenario simulations requires very large ensembles. A computationally cheaper alternative implemented in this study consists of performing two 250-year-long atmosphere-ocean coupled simulations with EC-EARTH 3.3 (CMIP6 version) with fixed radiative forcing at the years 2000 and 2050, representative of present and future climate conditions, respectively. The changes in the leading modes of Tropical Atlantic variability (TAV), including the Atlantic Niño/Niña and the Subtropical North Atlantic pattern, have been assessed in three target seasons: spring (MAM), summer (JJ) and early winter (ND). While the change in sea surface temperature (SST) climatology shows homogeneous warming, the difference between future and present SST variability exhibits a distinct behaviour consistent along the seasonal cycle, with a decrease in the equatorial region and an increase at subtropical latitudes. This study explores the processes associated with the suppressed/enhanced TAV, with a particular focus on the less-explored early winter season. In agreement with previous studies, the Atlantic Meridional Overturning Circulation (AMOC) shows a weakening in strength, but the results also show an increase in variability. The AMOC-related deepening of the equatorial thermocline and the flattening linked to weakened trade winds are consistent with the suppressed SST variability of the Atlantic Niño/Niña. On the other hand, the enhanced SST variability at subtropical latitudes is mainly associated with an increase in turbulent heat flux variability, with a minor contribution of the mixed layer depth variability. Variability in turbulent heat flux is influenced primarily by latent heat flux, connected to changes in precipitation variability.

Keywords Tropical Atlantic variability · Atlantic Niño · Subtropical North Atlantic

1 Introduction

The tropical Atlantic Ocean impacts the climate of the surrounding continents affecting human population: agriculture over northeastern Brazil and in the Sahel region, for example, is affected by rainfall fluctuations (Moura and Shukla 1981; Rowell et al. 1995); sea surface temperature (SST) changes affect fisheries (Thiaw et al. 2017). The tropical Atlantic variability (TAV) also influences remote areas, with impacts on summer European temperature (Mohino and Losada 2015), rainfall over the Indian monsoon region (Kucharski et al. 2007), and North Atlantic hurricanes (Wang et al. 2006). The challenge in understanding TAV relies on disentangling the effect of multiple competing influences originating both from local and remote processes (Sutton et al. 2000).

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The SST variability in the tropical Atlantic is controlled by the annual cycle, which is tied to the asymmetry with respect to the equator (such as the northward-displaced inter-tropical convergence zone -ITCZ-) and has the following characteristics [see Xie and Carton (2004) for a review]: the equatorial Atlantic reaches its maximum temperature during boreal spring when the equatorial winds are the weakest, and the thermocline is the deepest. This season also experiences the maximum incident solar radiation; the ITCZ over the ocean is close to the equator, where the easterly trades converge from both hemispheres and SST is uniformly warm in the equatorial zone. With the onset of the West African monsoon in May–June, the ITCZ moves to the north and the southerly trade winds intensify, leading to a shoaling of the equatorial thermocline. In July, the SST reaches its minimum along the equator associated with upwelling and evaporation. In July–August, a cold tongue forms across the basin, which spreads to the west due to easterly wind induced by the ocean–atmosphere interaction (Okumura and Xie 2006). The equatorial ocean slowly warms up after the cold tongue reaches its peak.

In addition to these seasonal variations, there are recurrent SST anomalies with coherent structures, taking place in narrow time windows. These are connected with changes in the trade winds and SST anomalies and are identified as two ocean–atmosphere modes: the equatorial zonal mode, known as Atlantic Niño/Niña (AtlN), and the meridional mode, so-called Subtropical North Atlantic (SNA) pattern. The AtlN is similar to the Pacific El Niño–Southern Oscillation (ENSO), which mainly results from the Bjerknes feedback, where the interaction of subsurface heat content, SST and zonal winds along the equator are at play (Bjerknes 1969; Philander 1986; Zebiak 1993). Specifically, warm SST anomalies in the eastern equatorial Atlantic relax tropical trade winds, while cold SST anomalies accelerate them. In addition, westerly (easterly) wind anomalies induce ocean downwelling (upwelling) and deepening (shoaling) of the thermocline. The AtlN typically has an amplitude of 0.5°C and a frequency of approximately 2–3 years (Deser et al. 2010). It is more pronounced in boreal summer (June–July, JJ) and has a secondary peak in early winter (November–December, ND) which, only recently with the study of Okumura and Xie (2006), was shown to be statistically independent of its summer counterpart and of ENSO.

The SNA pattern is characterised by a meridional SST and surface pressure gradient between the northern and southern trade wind regions (Kushnir et al. 2006). Although strong feedback between SST, wind stress and surface heat flux are at play, the SNA pattern is not strictly a coupled mode of ocean–atmosphere variability (Sutton et al. 2000). The SNA is mainly driven by changes in the trade winds, and is amplified and maintained by the wind–evaporation–SST

(WES) feedback (Xie 1999; Amaya et al. 2017; Cabos et al. 2019). When the trades north of the equator are weakened, evaporation is reduced, resulting in increased SST, further weakening the trade winds (Ruiz-Barradas et al. 2000; Xie and Carton 2004). The opposite occurs during the cold phase. Some studies have debated whether the different hemispheric centres of action should be considered as two independent modes of variability [e.g. Dommenget and Latif (2000)], but in any case, the meridional mode represents a cross-equatorial SST gradient. The SNA pattern peaks in March–April–May (MAM), although the variability rises in early winter (ND).

The first objective of this study is to assess the capability of the CMIP6 version of the global climate model EC-EARTH to reproduce the leading modes of TAV, which has not been comprehensively assessed so far. While attention is given to the seasons of maximum SST variability, namely boreal spring (MAM) and summer (JJ), special focus will also be devoted to early winter (ND), which is generally less documented. A successful representation of TAV during this season has the potential to improve the prediction skill of winter forecasts in the North Atlantic–European region (e.g. Frankignoul and Kestenare 2005; García-Serrano et al. 2008). The second goal of this study is to investigate how SST variability in the tropical Atlantic may change under future climate conditions. To evaluate the effects of global warming, standard transient historical and scenario simulations are commonly used. However, these simulations do not allow isolating how the radiative forcing affects the variability, as the climate undergoes concurrent changes in response to evolving radiative forcing. Thus, there is a need for a large enough sampling to characterise the variability, which is achieved with the use of a large ensemble of simulations. A computationally cheaper alternative implemented in this work consists of performing two 250-year-long atmosphere–ocean coupled simulations, with fixed radiative forcing at the years 2000 and 2050, representative of present and future climate conditions, respectively. These two simulations with fixed radiative forcing are not equivalent to a large ensemble of transient simulations, but they can serve the scope of comparing the SST variability in the tropical Atlantic under different radiative forcing, as they provide 250 representations of the present and near-term future conditions respectively. The remainder of the paper is organized as follows. Section 2 describes the experimental setup, data, and methods used for the analysis. The performance of EC-EARTH 3.3 in reproducing TAV in the three target seasons is presented in Sect. 3.1, while Sect. 3.2 addresses the impact of the radiative forcing on TAV. Finally, Sect. 4 summarises of the conclusions drawn from our study.

2 Methods and data

2.1 Model description and experimental setUp

The study employs the state-of-the-art EC-EARTH climate model version 3.3 (Döscher et al. 2021) in its coupled configuration. Its atmospheric component is the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System (IFS) cycle 36r4 in its standard resolution, with 91 vertical levels and a T255 horizontal resolution (~ 80 Km). The ocean component is the NEMO model version 3.6 (Madec and NEMO System Team 2015), with ORCA1 configuration (about 1 degree with enhanced tropical resolution, ~ 100 Km) and 75 vertical levels. The sea-ice component is LIM3 (Rousset et al. 2015) directly embedded into NEMO. The atmospheric and ocean components are coupled via OASIS3 (Craig et al. 2017).

Two coupled simulations were run for 250 years after spin-up. This length was chosen to isolate and characterise the internal variability from the radiative forcing. The EC-EARTH present simulation started from a historical simulation, and the radiative forcing was kept constant at the year 2000, to be representative of the present condition. The EC-EARTH future simulation started from a projection with the SSP2–4.5 scenario (O'Neill et al. 2016), and it was run with a constant radiative forcing of the year 2050, also taken from the SSP2–4.5 scenario, to be representative of the near-term future climate, as commonly used in the Decadal Climate Prediction Project protocol [DCPP, Boer et al. (2016)].

2.2 Methodology

The region selection for the SNA is based on the domain definition from Rodríguez-Fonseca et al. (2006), 15° – 25° N; 20° – 30° W, while the AtlN is defined according to Okumura and Xie (2006) 3° S– 3° N; 5° – 15° W (purple boxes in Fig. 4). To identify the main patterns of variability, empirical orthogonal function analysis (EOF, e.g. Deser et al. (2010); Ruiz-Barradas et al. (2000)) is the commonly used method. However, it has been suggested by Dommenget and Latif (2000) that some of the patterns could result from an artefact of the EOF analysis technique due to its orthogonality constraint. The EOF analysis of SST anomalies in the tropical Atlantic from the EC-EARTH present simulation revealed limited differentiation among the variability modes. Of the three target seasons examined in this study, a suitable separation of the variability into two distinct patterns was only achieved in ND as shown in Fig. 12 of the Appendix. Therefore, in this

study, the indices have been calculated as the standardised weighted area averages of the detrended SST anomalies in the respective regions. For verification purposes, the HadISST (Rayner et al. 2003) and ERSST (Huang et al. 2020) observational datasets have been used for sea surface temperature. The observed climatologies are calculated from 1960 to 2020. The 95% confidence interval for the difference in climatologies has been calculated using a T-test for equal means. The variability of the field has been calculated as its standard deviation, and when the difference in variability is shown, a 95% confidence interval has been calculated following an F-test for equal variances. The statistical significance of the regression maps has been determined using a two-tailed student's T-test for correlation.

3 Results

3.1 EC-EARTH behaviour in present conditions

We begin our analysis by evaluating the annual cycle of SST climatology and variability in the SNA and AtlN domains (Fig. 1). In the AtlN region, the EC-EARTH-present simulation (blue line) accurately reproduces the main peak of variability in summer (particularly in July) and the second peak in early winter (November, bottom right panel of Fig. 1), displaying an annual cycle of SST variability that is captured more accurately than that of the SNA region (top right panel). This is despite the greater bias in the AtlN domain (left column). The bias of EC-EARTH is consistent with the warm bias of the CMIP6 ensemble average in the AtlN domain and in the eastern equatorial Atlantic, previously documented in Richter and Tokinaga (2020). In the SNA region, the major peak of SST variability in MAM is underestimated (top right panel of Fig. 1), although the climatology closely follows the observed annual cycle (top left panel). We will explore the behaviour of EC-EARTH future simulation in section 3.2.

We assess the ability of EC-EARTH to accurately reproduce the spatial patterns associated with AtlN and SNA modes in their respective major peaks of variability. During MAM, EC-EARTH accurately reproduces the characteristic SST pattern (top left panel in Fig. 2) associated with the SNA mode, with warm anomalies along the whole basin at subtropical latitudes and a meridional temperature gradient. The trades are weakened (top left panel in Fig. 2) and the ITCZ is shifted northward (top right panel Fig. 2). In the extratropics, the SST exhibits a horseshoe structure and the precipitation displays a dipolar structure with opposite behaviour, which resembles the pattern linked to the NAO negative phase. During JJ, the SST shows warm anomalies in the Gulf of Guinea, which are characteristic of the AtlN

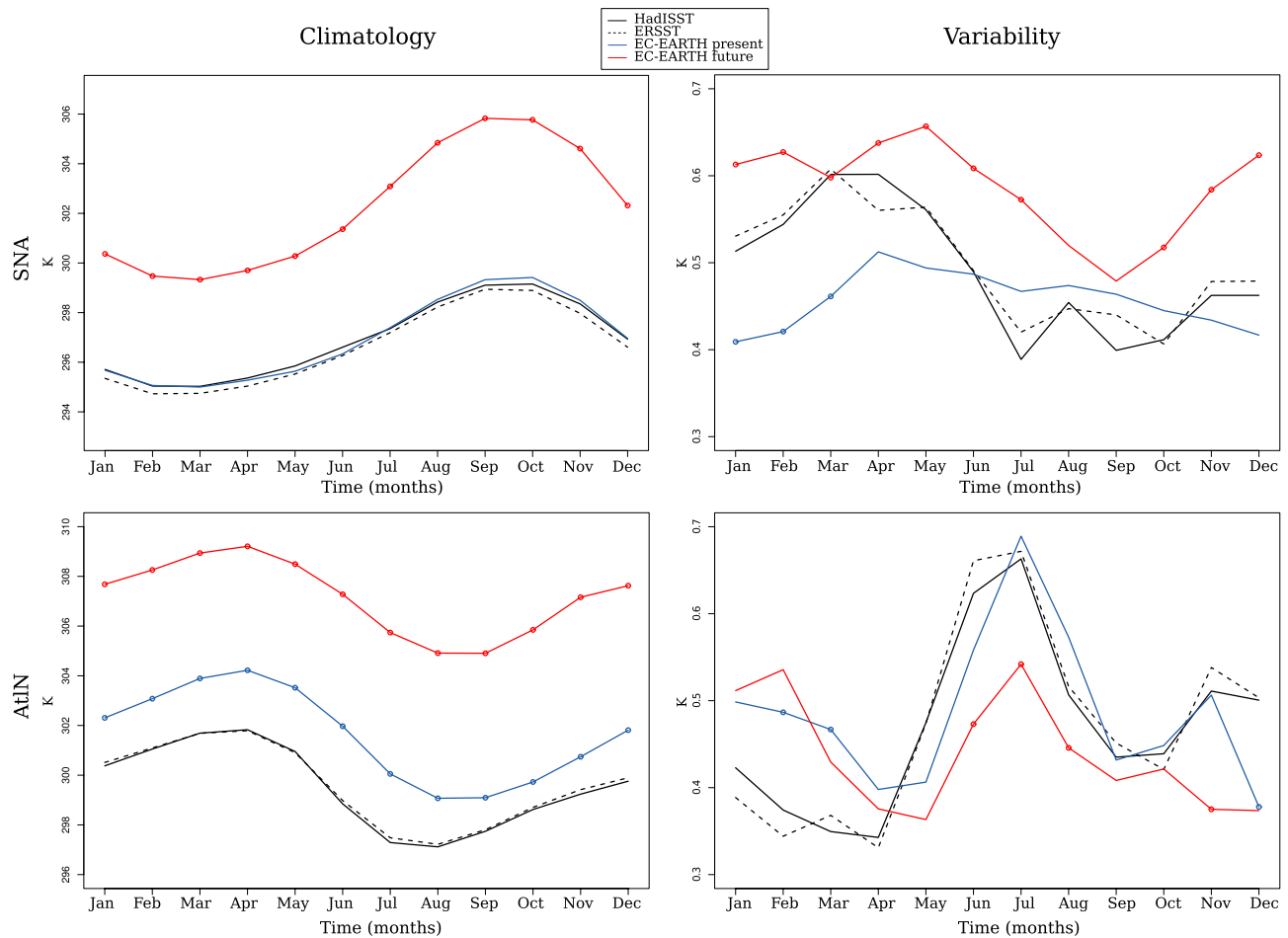


Fig. 1 Left column: annual cycle of the SST climatology in the Subtropical North Atlantic (top row) and the Atlantic Niño region (bottom row). Right column: annual cycle of the SST variability calculated as the interannual standard deviation of the SNA and AtIN indices. In black are shown respectively the HadISST (solid) and ERSST (dashed) datasets, in blue the EC-EARTH-present simulation

and in red the EC-EARTH-future simulation. The blue dots indicate when EC-EARTH-present is significantly different from the observational datasets at a 95% confidence level following a T-test for equal means (left column) and an F-test for equal variances (right column). Similarly, the red dots indicate when EC-EARTH-future is significantly different from EC-EARTH-present at a 95% confidence level

mode; these anomalies are accompanied by strong wind anomalies, which converge towards the maximum of the SST (as depicted in the bottom left panel of Fig. 2). Additionally, there is a southward shift in the Eastern Atlantic tropical convection (bottom right panel of Fig. 2). These patterns are consistent with those found in previous observational studies, such as Ruiz-Barradas et al. (2000) and Okumura and Xie (2006).

Figure 3 shows the spatial patterns of SST, wind (first column) and precipitation (second column) associated with the two variability modes in early winter (ND) for the EC-EARTH-present simulation. The SST anomaly pattern associated with the SNA displays a tripole structure with warm centres situated South of Greenland and in the subtropical Atlantic, and a cool centre in between. The precipitation

(top right panel of Fig. 3) exhibits a similar dipole as the one shown for the MAM peak in Fig. 2, shifted towards Europe. The SST, wind and precipitation patterns associated with AtIN in ND (second row of Fig. 3) are less intense than the ones shown for the JJ peak, yet they are consistent with the observational study of Okumura and Xie (2006).

3.2 Future conditions

This section examines the changes in TAV under future climate conditions. The annual cycle in Fig. 1 (red line) shows a warmer than present climatology in both domains, while maintaining a consistent annual cycle with the present condition (left column). Notably, the variability of SST increases in the SNA domain under future conditions, but decreases in the

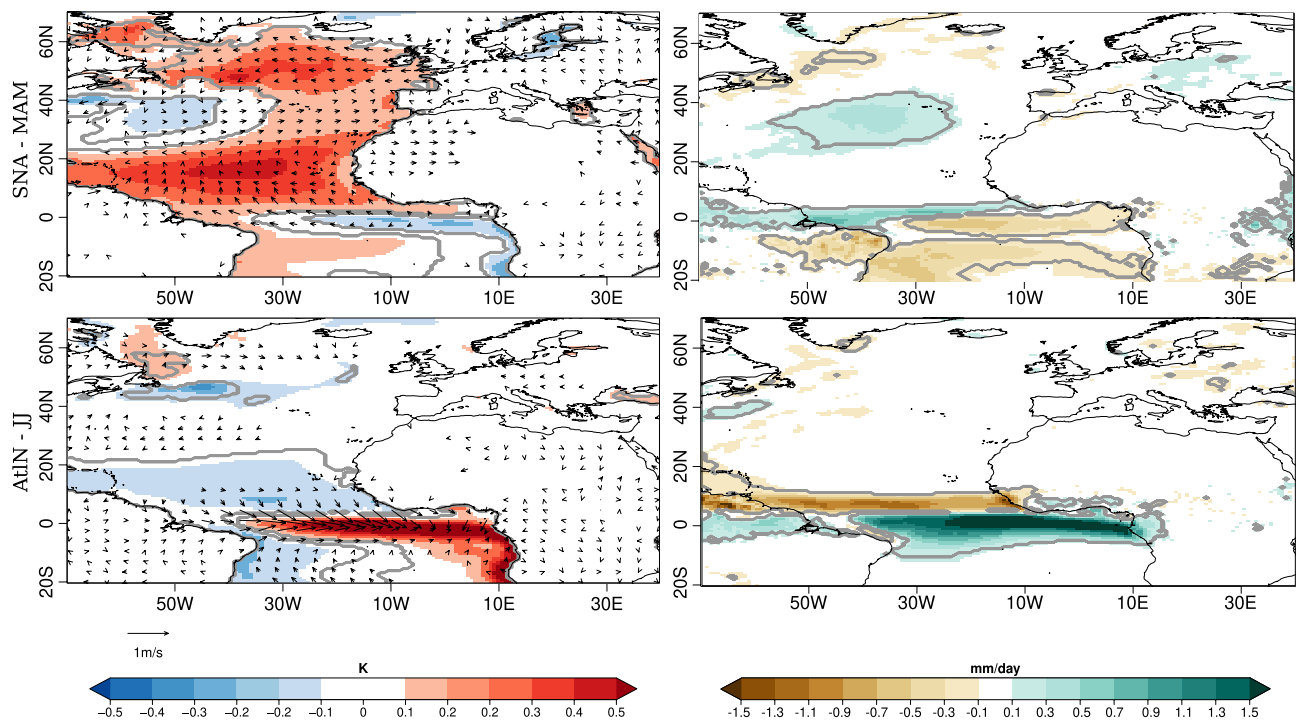


Fig. 2 Sea surface temperature, surface wind (left column) and precipitation (right column) regressions onto the SNA index in March–April–May (top row) and the AtN index in June–July (bottom row) for EC-EARTH-present simulation. The grey contours indicate statis-

tically significant regions at a 95% confidence level following a two-tailed student's T-test; arrows are shown (left column) when at least one component of the wind is statistically significant

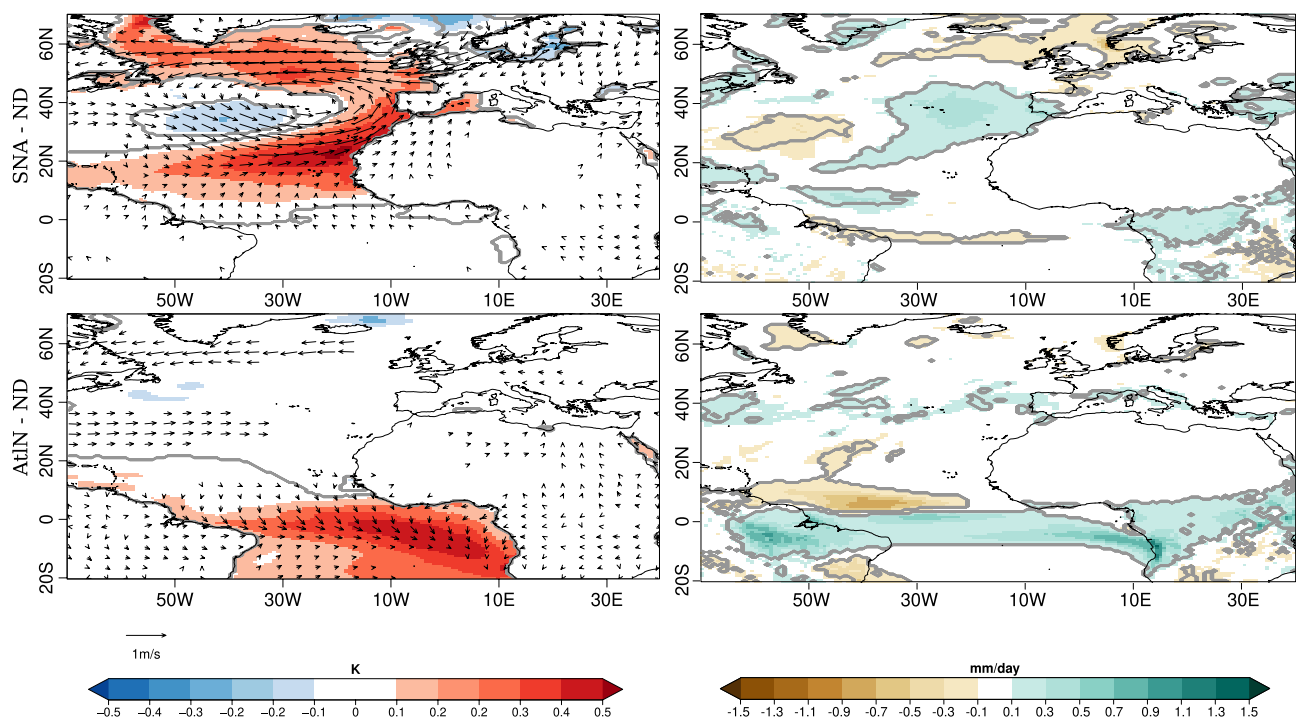


Fig. 3 Same as Fig. 2, but for November–December

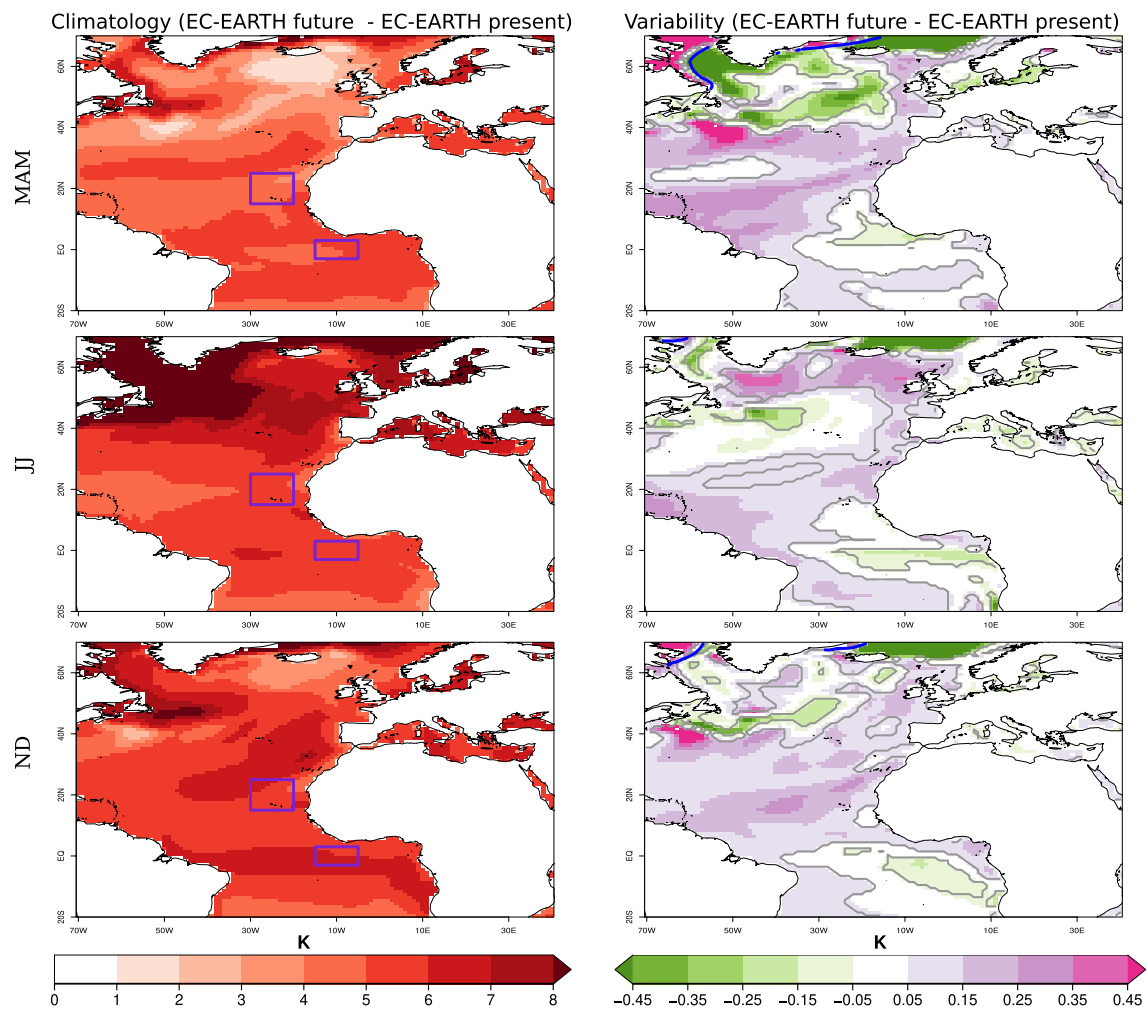


Fig. 4 Difference between future and present SST climatology (left column) and variability (right column) in MAM (top row), JJ (middle row) and ND (bottom row). The difference in climatology is statistically significant at a 95% confidence level in the whole domain following a T-test for equal means. The grey contours in the second column indicate statistically significant regions at a 95% confidence level

AtlN region (red lines in the right column of Fig. 1). To gain a more comprehensive understanding of this behaviour, Fig. 4 displays the two-dimensional differences in SST climatology (first column) and variability (second column) in MAM (top), JJ (middle) and ND (bottom). The results align with those depicted in Fig. 1, displaying a general warming in the future climate during the three seasons for both domains, though not evenly distributed. The high level of warming in certain regions (left column of Fig. 4) can be attributed to the high climate sensitivity of the model version used (Wyser et al. 2020). At high latitudes, the difference in climatology shows a warming hole for all target seasons (Keil et al. 2020), particularly evident in MAM. The AtlN region experiences a reduction in variability under future climate conditions, whereas the SNA domain an increase (right column of Fig. 4). During

following an F-test for equal variances. The blue contour shows the sea ice edge in present climate. Note that the sea ice edge of future climate is not visible because it falls out of the domain shown in the figure. Purple boxes in the left panels indicate the regions where SNA and AtlN indices were calculated

MAM, the SST variability reduces significantly in the Labrador and Norwegian seas in EC-EARTH future simulation, possibly due to the retreat of the sea ice edge. Along the coast of Guinea, there is little to no change in variability throughout the three seasons, likely due to the presence of upwelling in the region. In the Appendix, Figs. 13 and 14 of the Appendix show respectively the SST climatology and standard deviation for the HadISST dataset, EC-EARTH present and future simulations in MAM, JJ and ND seasons.

Figures 5 and 6 illustrate the impact of future conditions on the spatial pattern of SST, wind and precipitation associated with the SNA and the AtlN during their main peak seasons (respectively MAM and JJ) and in early winter (ND). During MAM, the SST anomalies associated with the SNA show an increase as seen in the top left panel of Fig. 5.

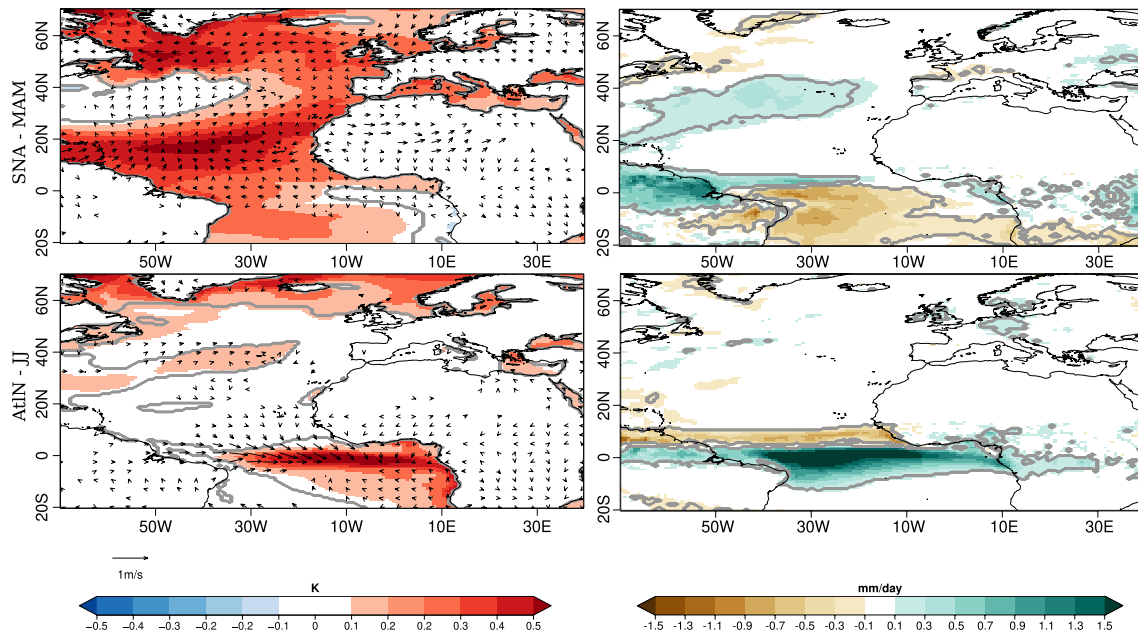


Fig. 5 Same as Fig. 2, but for the EC-EARTH-future simulation

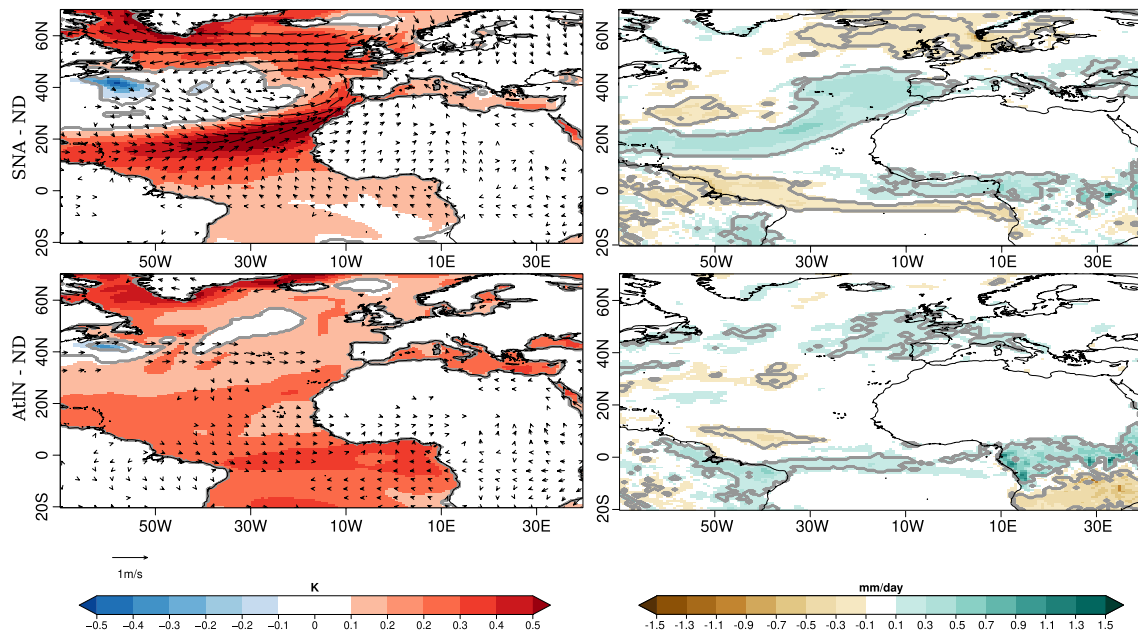


Fig. 6 Same as Fig. 3, but for the EC-EARTH-future simulation

Additionally, the precipitation anomalies intensify and extend over northern Brazil (top right panel). Conversely, during JJ the SST and wind anomaly patterns associated with the AtIN are weaker than present conditions (bottom left panel of Fig. 5). The precipitation anomaly patterns intensify over land, particularly over Brazil and central Africa (bottom right panel). There is still a southward shift

in the Eastern tropical convection, but in future conditions, the maximum precipitation is shifted towards the central/western part of the basin, due to the zonal SST gradient depicted in the middle left panel of Fig. 4. The results suggest that the same dynamics underlying TAV are also at play in future climate.

Similarly, during early winter (Fig. 6), there is an intensification of SST and wind anomalies associated with SNA. The convection zone is still shifted northward as in the present climate, and the significant precipitation anomalies expand over the whole subtropical basin, the coast of Brazil, central Africa and the Iberian peninsula (top right panel). The warm tongue that characterises the AtlN mode is difficult to detect in the regression map associated with AtlN in ND (bottom left panel of Fig. 6), as the warm anomalies expand throughout the entire basin. There is still a weakening of the trades and a southward shift of the convection zone (bottom right panel of Figure 6) as in the present climate. These changes in the spatial patterns under future conditions are consistent with the changes in variability described in Fig. 1.

Previous studies (Haarsma et al. 2008; Polo et al. 2013) have identified a connection between the weakening of the Atlantic Meridional Overturning Circulation (AMOC) -obtained through water hosing experiments- and the reduction of the AtlN variability. We therefore analyse the AMOC to gain a deeper understanding of the changes of TAV in future climate. Figure 7 illustrates the annual climatology of the AMOC (represented by shading) and its variability (represented by contours), respectively in the present climate (left panel) and the difference between future and present conditions (right panel). In the EC-EARTH future simulation, the AMOC experiences a weakening in climatology, rendering it more susceptible to changes and increasing variability. This could explain part of the North Atlantic SST increase of variability shown in Fig. 4. The weakening in the climatology of the AMOC could explain the warming hole in the SST climatology of Fig. 4, linked to the decrease of the northward oceanic heat transport (Bellomo et al. 2021). Furthermore, the

freshwater linked to sea-ice reduction, as shown by the decreased variability in SST depicted in the right column of Fig. 4, may play a role in the weakening of the AMOC. However, evaluating the AMOC changes under future conditions falls beyond the scope of this study.

As mentioned in the Introduction, the early winter TAV is less documented. Hence, the rest of this study focuses on the ND season, for its potential role in improving winter seasonal predictions.

Fig. 8 shows the variability of the ocean temperature profile in the EC-EARTH present simulation (left row) and the difference between the present and the future simulation (right column) in ND. In the equatorial region (bottom panels), the present simulation shows high variability of temperature around the tilted thermocline (solid blue line), which is shoaled towards the West African coast, while the future simulation shows a flattened and deepened thermocline (red line right panels). These results align with Crespo et al. (2022)'s findings on the summer AtlN. As suggested by Haarsma et al. (2008), the deepening of the thermocline could be connected to the collapse of the AMOC seen in Fig. 7 and the reduction of cold water upwelling in the equatorial Atlantic. As a consequence of the deepening, the sensitivity of the thermocline to zonal wind stress variations is reduced. In turn, the SST remains unaffected by changes in the thermocline (Polo et al. 2013), resulting in a decoupling of the eastern Atlantic surface water and the underlying ocean. This reduces the effectiveness of one of the components of the Bjerknes feedback. As summarised in Deppenmeier (2022) these changes, together with the increased stability of the tropical Atlantic atmosphere seems to contribute to the weakening of the Bjerknes feedback, leading to the suppression of the AtlN (Yang et al. 2022).

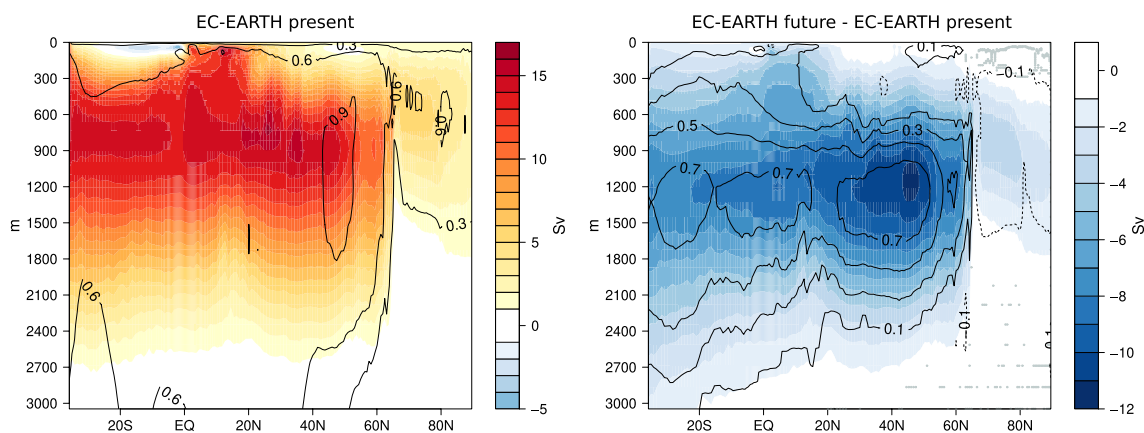


Fig. 7 Climatology (in shading) and variability (in contours) of the Atlantic overturning stream function calculated with annual values. The left panel displays EC-EARTH-present, while the right panel shows the difference between the future and present EC-EARTH

simulations. Grey dots in the right column indicate non-significant regions following a T-test for equal means at a 95% confidence level, while the difference in variability is statistically significant in the whole domain following an F-test for equal variances

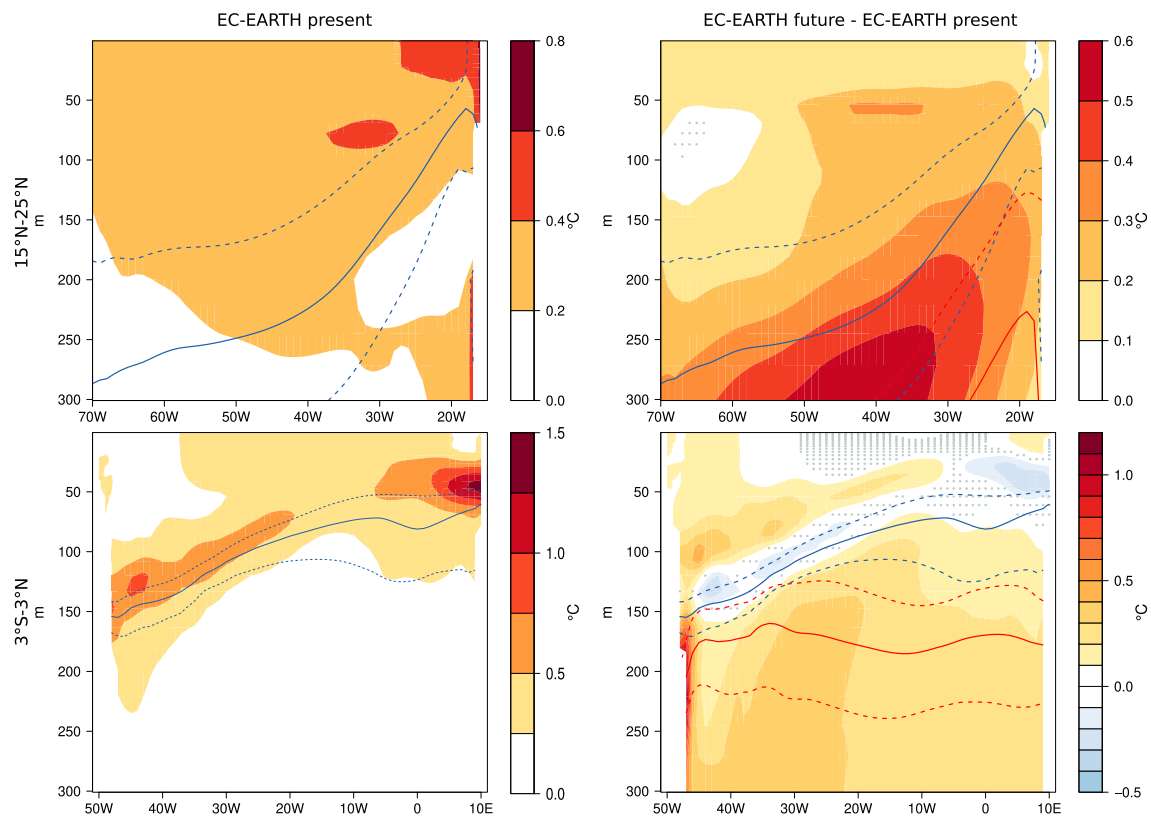


Fig. 8 Profile of ocean temperature variability (in shading) for November–December in the subtropical North Atlantic basin (top row, 15° – 25° N) and the equatorial basin (bottom row, 3° S– 3° N). The left column displays EC-EARTH-present while the right column shows the difference between the future and present

EC-EARTH simulations. The solid lines depict the isotherm of 20° C in the present (blue) and future (red) simulations, while the dashed lines represent the 18° C and 22° C isotherms. Grey dots in the right column indicate non-significant regions following an F-test for equal variances at a 95% confidence level

Conversely, in the subtropical band (first row of Fig. 8), there is an increase of variability in the upper ocean despite the thermocline deepening.

Haarsma et al. (2008) noted that SNA is not significantly modified by changes in the AMOC because it is mainly forced by atmospheric fluxes.

To investigate possible sources of the increased variability of upper ocean temperature in the subtropical band, we examine surface processes. The top row of Fig. 9 shows the difference in mixed layer depth (MLD) climatology (left column) and variability (right column) between future and present simulations in ND. The MLD of ND under future conditions displays a shallower climatology and reduced variability compared to present conditions, which is consistent with the SST warming shown in Fig. 4. This is further supported by the weakening of surface wind depicted in the middle row of Fig. 9, which exhibits a weaker climatology and decreased variability in future conditions. The climatological weakening of trades in the equatorial band could explain the flattening of the thermocline shown in the

bottom row of Fig. 8, as previously suggested in the studies of Crespo et al. (2022) and Yang et al. (2022) for the JJ season.

The bottom row of Fig. 9 shows a significant increase in upward turbulent heat flux (THF, positive values in the map) in the future climatological state, as well as an increase in variability in the subtropical band. Such an increase in THF variability could explain the increased temperature variability shown in the upper subtropical ocean (top right panel of Fig. 8). In particular, the latent heat flux is the main contributor to the increased exchange of ocean–atmosphere fluxes, as shown in the top panels of Fig. 10. Following the results by Breugem et al. (2007) where the latent heat flux change was decomposed in different contributors, the reduction in surface wind variability seems to contradict the increased variability in latent heat flux. However, Fig. 11 reveals that the latter can be explained by the rise in precipitation variability in the subtropical band (as shown in the right panel). Conversely, the reduction in THF variability in the North Atlantic is mainly due to the reduction of sensible heat flux variability (bottom panels of Fig. 10), a factor that may also

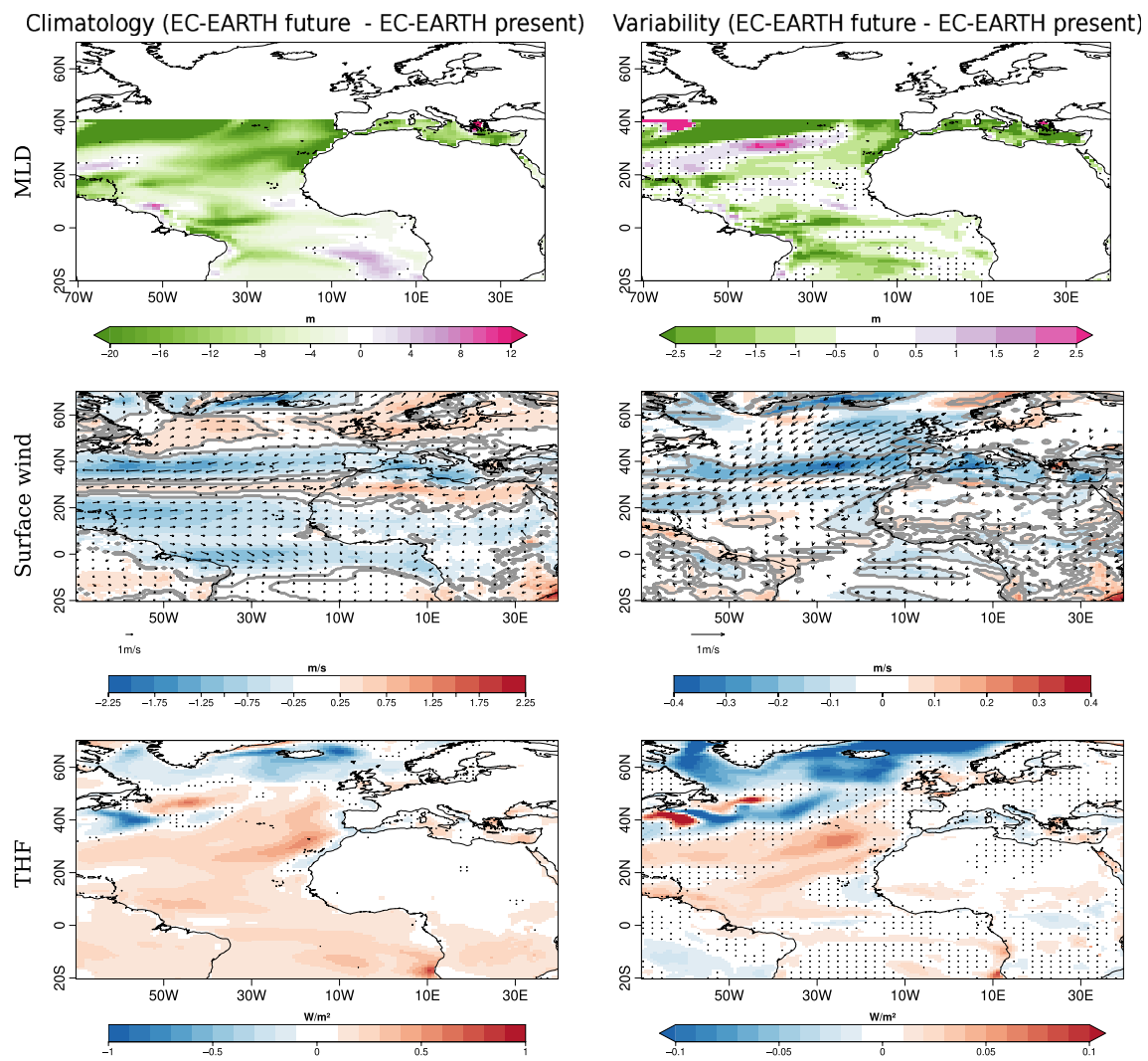


Fig. 9 Difference between future and present climatology (left column) and variability (right column) for the mixed layer depth (top row), surface wind (middle row) and turbulent heat flux (bottom row)

in November–December. Black dots indicate non-significant regions following a T-test for equal means (left column) and an F-test for equal variances (right column) at a 95% confidence level

contribute to the loss of SST variability in that region (as illustrated in the bottom right panel of Fig. 4 for ND). Additionally, the climatological state of precipitation (as depicted in the left panel of Fig. 11) exhibits an equatorial shift of the ITCZ, which is mirrored by an increase of variability in the equatorial band.

4 Summary and conclusions

This study evaluates the ability of EC-EARTH version 3.3, specifically the CMIP6 version of the model, to simulate the Tropical Atlantic variability (TAV) and its main modes, namely the Atlantic Niño/Niña (AtlN) and the Subtropical North Atlantic (SNA) pattern. In addition, the study investigates the impact of radiative forcing (global warming) on

TAV. These objectives are accomplished through the analysis and comparison of two 250-year-long coupled simulations with fixed radiative forcing at the years 2000 and 2050, representing present and future climate conditions, respectively. Our analysis has led to the following findings:

- Although EC-EARTH exhibits a marked warm bias in the equatorial Atlantic, it accurately captures the annual cycle of the AtlN variability, simulating its two peaks, in summer (June–July) and early winter (November–December).
- While the simulated sea surface temperature (SST) climatology in the SNA domain closely follows the observed annual cycle, its variability is generally underestimated, although the model yields a maximum in spring (March–April–May).
- EC-EARTH properly simulates the spatial patterns of SST, surface wind, and precipitation that are associated with AtlN

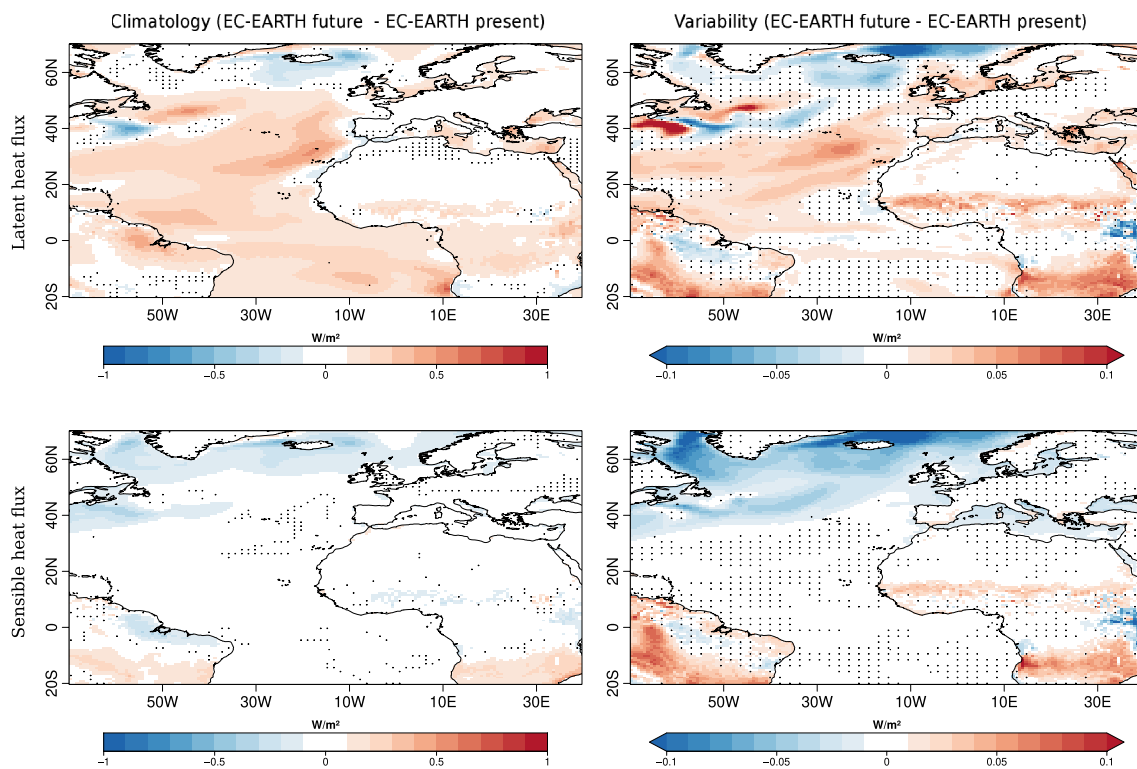


Fig. 10 Difference between future and present climatology (left column) and variability (right column) for latent heat flux (top row) and sensible heat flux (bottom row) in November–December. Black dots

indicate non-significant regions following a T-test for equal means (left column) and an F-test for equal variances (right column) at a 95% confidence level

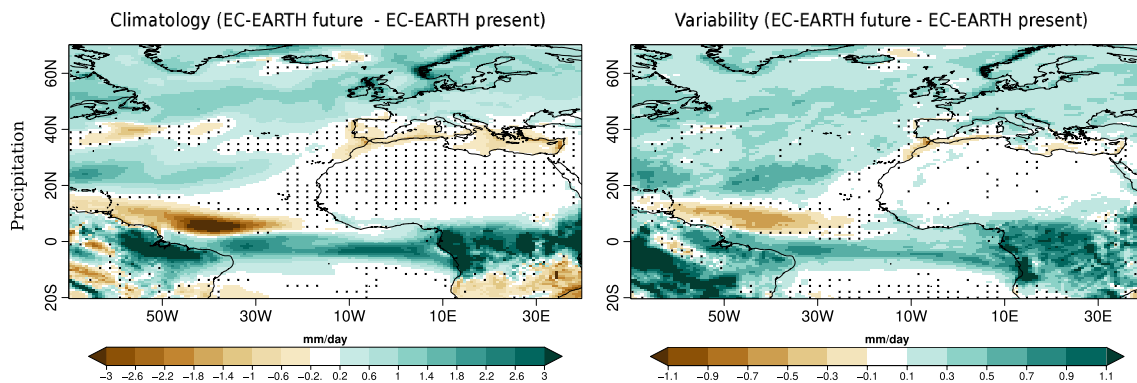


Fig. 11 Difference between future and present climatology (left column) and variability (right column) for precipitation in November–December. Black dots indicate the no-significant regions following a

T-test for equal means (left column) and an F-test for equal variances (right column) at a 95% confidence level

and SNA during the seasons of their primary variability peaks, namely June–July and March–April–May respectively, as well as early winter (November–December).

- Under future climate conditions, the variability of SNA increases while the one of AtIN decreases.
- The analysis of the spatial pattern of SST, surface wind, and precipitation associated with AtIN and SNA under future radiative forcing suggests that the same underlying dynamics driving TAV are also at play in future climate.

- Consistent with the findings of Crespo et al. (2022) and Yang et al. (2022) for June–July, our results show that the suppression of AtIN variability in November–December under future climate conditions can be linked to the decoupling between the eastern equatorial Atlantic surface water and the underlying ocean. Specifically, under future conditions, the deepening and flattening of the equatorial thermocline reduces its sensitivity to variations in zonal wind stress. The weakening of the equatorial trade winds could explain the

flattening of the thermocline in the eastern Atlantic. The deepening of the equatorial thermocline may be linked to the weakening of the Atlantic Meridional Overturning Circulation (AMOC), as previously shown by water hosing experiments conducted by Haarsma et al. (2008) and Polo et al. (2013). In turn, SST variability remains unaffected by changes in the thermocline. This, together with the increased stability of the tropical Atlantic atmosphere, contribute to the weakening of the Bjerknes feedback, leading to a decrease of the AtlN variability.

- In future climate conditions, the enhanced SST variability in November–December over the subtropical North Atlantic

appears to be dominated by the increase in variability of the turbulent heat flux. The increased exchange in ocean–atmosphere heat flux is mainly due to the latent heat flux, with the specific humidity component dominating over the surface wind component. The former is consistent with the rise in precipitation variability over the region.

Appendix

See Figs. 12, 13 and 14.

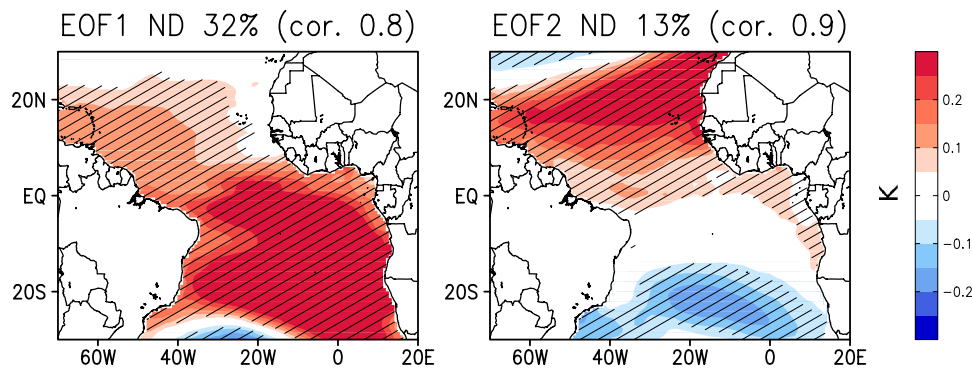
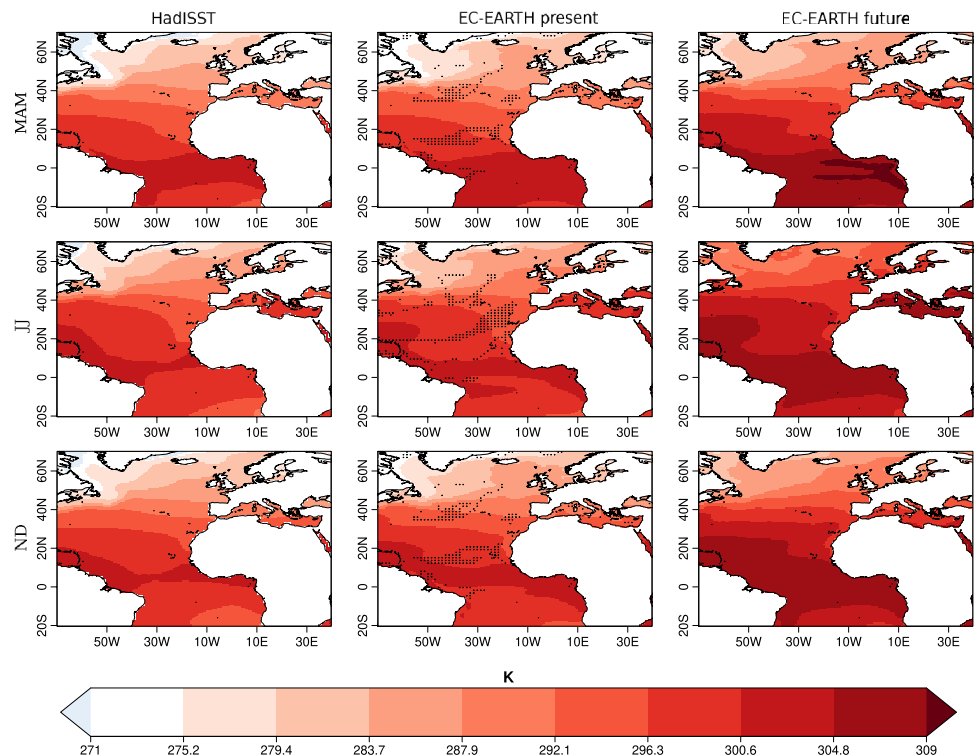


Fig. 12 First (left panel) and second (right panel) empirical orthogonal functions (EOFs) of detrended monthly SST anomalies in the tropical Atlantic Ocean based on SST from EC-EARTH present simulation for ND. The title of each panel indicates the respective frac-

tions of variance (%) and the correlation with the AtlN index (left panel) and the SNA index (right panel). Hatching indicates statistically significant regions at a 95% confidence level following a two-tailed student's T-test

Fig. 13 SST climatology for HadISST dataset (first column), EC-EARTH present (second column) and EC-EARTH future (third column) simulations. The first row represents the season March–April–May, the middle row is for the months June–July and the bottom row is for November–December. The dots in the middle column represent the areas where the model bias is not significant following a T-test for equal means with a 95% confidence interval



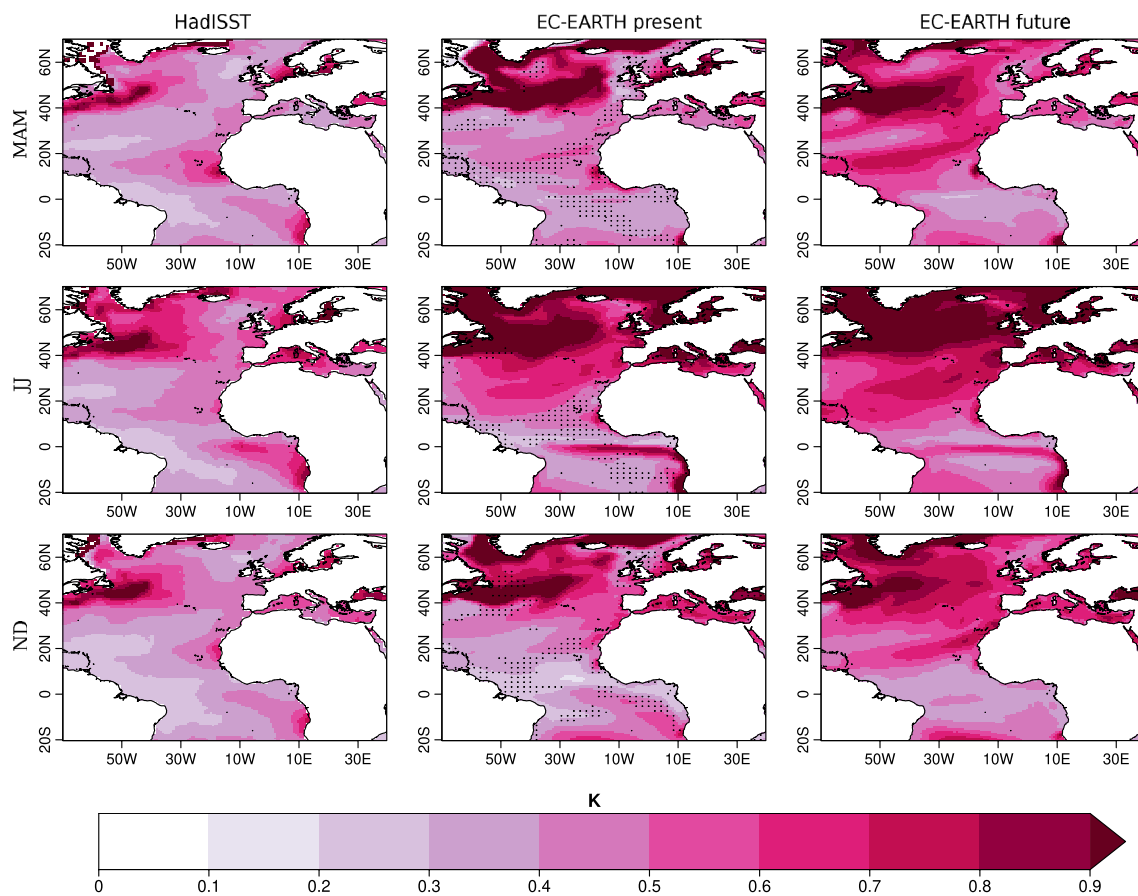


Fig. 14 SST standard deviation for HadISST dataset (first column), EC-EARTH present (second column) and EC-EARTH future (third column) simulations. The first row represents the season March–April–May, the middle row is for the months June–July and the bottom

row is for November–December. The dots in the middle column represent the area where the model variability is not significantly different from the observed variability following an F-test for equal variances with a 95% confidence interval

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Author Contributions JG-S and FMP designed the experiments. FMP ran the simulations. DV performed the analysis. All the authors contributed to the discussion and the interpretation of the results. DV wrote the manuscript with the contribution and the approval of all co-authors.

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Data availability statement The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflict of interest.

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