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Key Points:

- Since 2000, the March-April-May sea surface temperature variability has weakened by more than 30% in the Angola-Benguela area
- Since 2000, the equatorial remote forcing has less influence on Angola-Benguela sea surface temperatures
- Since 2000, the Angola-Benguela local forcing is likely to impact the surface layer more due to a shallower stratification maximum

Supporting Information:

- Supporting Information S1

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Origin of Weakened Interannual Sea Surface Temperature Variability in the Southeastern Tropical Atlantic Ocean

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Abstract Observations and reanalysis products are used to investigate the substantial weakening in the southeastern tropical Atlantic sea surface temperature (SST) variability since 2000. Relative to 1982–1999, the March–April–May SST variability in the Angola–Benguela area (ABA) has decreased by more than 30%. Both equatorial remote forcing and local forcing are known to play an important role in driving SST variability in the ABA. Compared to 1982–1999, since 2000, equatorial remote forcing had less influence on ABA SSTs, whereas local forcing has become more important. In particular, the robust correlation that existed between the equatorial zonal wind stress and the ABA SSTs has substantially weakened, suggesting less influence of Kelvin waves on ABA SSTs. Moreover, the strong correlation linking the South Atlantic Anticyclone and the ABA SSTs has reduced. Finally, multidecadal surface warming of the ABA could also have played a role in the weakening of the interannual SST variability.

Plain Language Summary Every few years, the southeastern tropical Atlantic Ocean experiences anomalous sea temperatures that affect fisheries and rainfall. Using observations and reanalysis data, we quantify the Angola–Benguela area (ABA) sea surface temperature (SST) variability during the last decades. Relative to 1982–1999, the March–April–May SST variability in the ABA has decreased by more than 30% since 2000. Remote equatorial forcing through equatorially and coastally trapped oceanic waves and variations in the local winds are the main drivers of ABA SST variability. Since 2000, we find that ABA SSTs are less connected to equatorial winds and exhibit a weaker link with the South Atlantic Anticyclone. Finally, the surface warming of the ABA observed during the post-2000 period also could have played a role in the weakening interannual SST variability.

1. Introduction

The tropical Atlantic Ocean sea surface temperatures (SSTs) have warmed substantially over the last decades (Servain et al., 2014; Tokinaga & Xie, 2011; Vizy & Cook, 2016) and particularly in the southeastern tropical Atlantic. In association with the basin-wide warming, which is most pronounced in boreal summer reducing the annual cycle through a positive ocean-atmosphere feedback, a strong reduction of the equatorial Atlantic SST variability was reported by Tokinaga and Xie (2011) over the period 1950–2009. However, multidecadal variability is large. Nnamchi et al. (2020) found that SSTs during the satellite era 1979–2018 exhibit a warming hole over the equatorial Atlantic cold tongue region in boreal summer. This lack of surface warming denotes an 11% amplification of the mean SST annual cycle in that region. Recently, Prigent et al. (2020), using observations and reanalysis products, found that the equatorial Atlantic interannual SST variability in May–June–July has reduced by 31% during 2000–2017 relative to 1982–1999. Interannual SST variability in the equatorial Atlantic and Angola–Benguela area (ABA) are strongly connected (Hu & Huang, 2007; Lübbecke et al., 2010; Reason et al., 2006). Hence, it may well be that the SST variability in the southeastern tropical Atlantic also has undergone a reduction since 2000, which is the topic of this study.

SSTs along the coasts of Namibia and Angola are characterized by a strong seasonal cycle, with warmest SSTs in March–April–May (MAM), modulated by variability from subseasonal to decadal time scales (Bachelery et al., 2019). The main features of interannual SST variability over the ABA (8°E to the coast; 10–20°S, blue box in Figure 1a) are warm and cold events, the so-called Benguela Niños and Benguela Niñas (Shannon et al., 1986), respectively. Anomalous surface temperatures along the coasts of Angola and Namibia, typically lasting for a few months and peaking in MAM, impact the regional climate (Hansingo & Reason, 2009;

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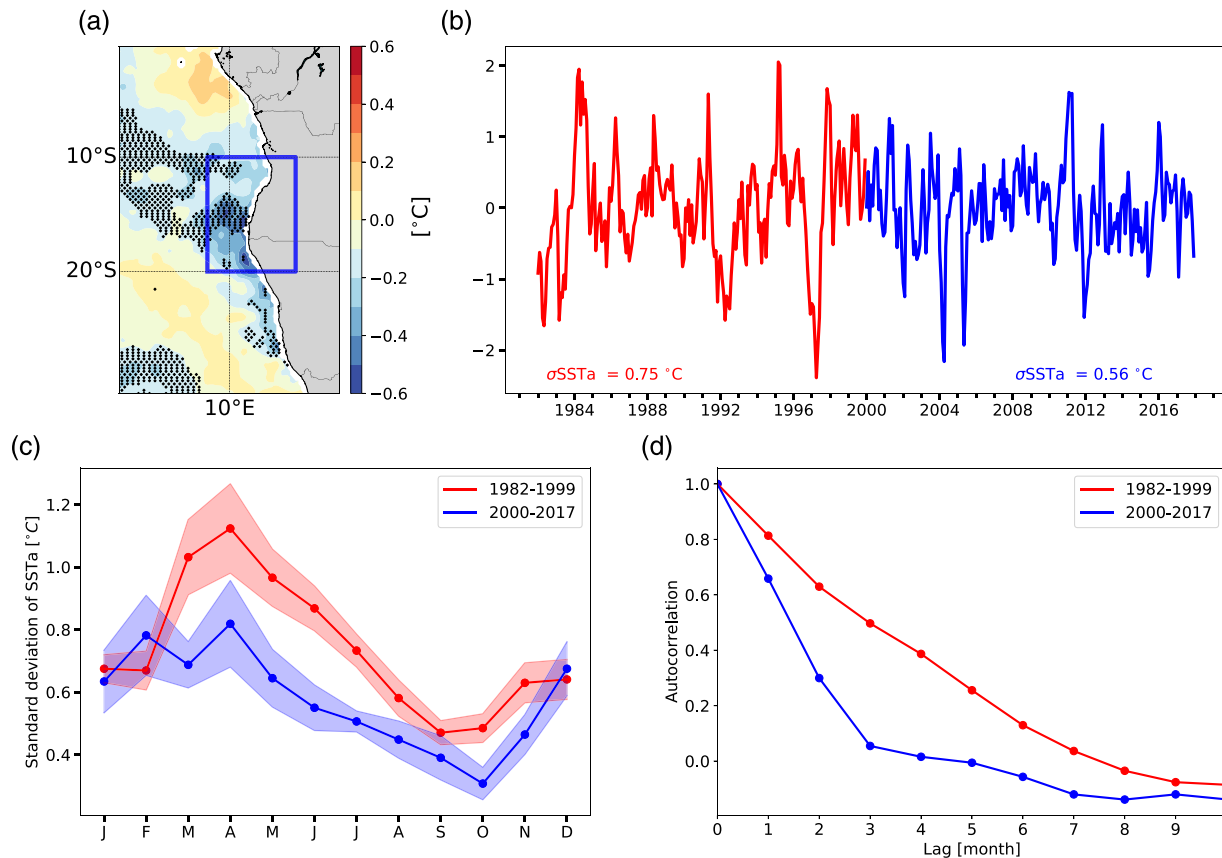


Figure 1. (a) Difference of MAM SST anomalies (SSTa) standard deviation between 2000–2017 and 1982–1999 from ERA5. Dots indicate where the standard deviations between the two periods are significantly different at the 95% level according to a Welch's *t* test. (b) Time series of monthly ABA-averaged ERA5 SSTa. (c) Ensemble mean standard deviation of ABA-averaged SSTa as function of the calendar month during 1982–1999 (red) and 2000–2017 (blue). The six SST products used are indicated in Table S1. (d) Autocorrelation function of the monthly ABA SSTa during 1982–1999 (red) and 2000–2017 (blue).

Koseki & Imbol Koungue, 2020; Lutz et al., 2013; Rouault et al., 2003, 2007) as well as marine ecosystems and fisheries (Bachelery et al., 2016, 2019; Binet et al., 2001; Gammelsrød et al., 1998).

Such events are mainly driven by two mechanisms: (1) remote forcing from the equatorial Atlantic and (2) local atmospheric forcing. The remote forcing is associated with the fluctuations of the trade winds over the western and central parts of the equatorial Atlantic, triggering eastward propagating equatorial Kelvin waves (EKWs). When reaching the West African coast, part of the energy of the EKWs is transmitted poleward along the West African coast (Polo et al., 2008) as coastally trapped waves (CTWs; Clarke, 1983), which affect local stratification, SST, alongshore currents, and biogeochemical conditions (Bachelery et al., 2015, 2016, 2019; Illig & Bachelery, 2019; Illig, Bachelery, & Cadier, 2018; Illig, Cadier, et al., 2018; Rouault, 2012; Rouault et al., 2018). Bachelery et al. (2019) showed in an ocean modeling study that remote forcing from the equatorial Atlantic explains around 50% (70%) of the interannual SST (sea level anomaly) variability between 10°S and 20°S along the West African coast. Richter et al. (2010) showed, using observations and a coupled general circulation model, that Benguela Niños also can be forced by weakened local alongshore winds related to the strength of the South Atlantic Anticyclone (SAA). Moreover, Lübbecke et al. (2019) have demonstrated that the warm event of 2016 off Angola and Namibia was generated by a combination of local processes, that is, reduction of alongshore winds and local upwelling, anomalous heat fluxes, freshwater input, and meridional advection.

Predicting SSTs in the ABA is challenging. Two predictors have been suggested: (1) an index based on SAA strength (Lübbecke et al., 2010) and (2) an index based on EKW activity (Imbol Koungue et al., 2017). Both approaches would allow to predict Benguela Niño and Benguela Niña events at 1 to 2 months lead time.

In this study, we document a marked reduction of the interannual SST variability in the ABA since 2000. Possible links to remote forcing from the equatorial Atlantic and to the SAA and implications for the predictability of Benguela Niños and Benguela Niñas are discussed.

2. Data and Methods

2.1. Data

2.1.1. Ocean Reanalyses

Three ocean reanalysis SST products with monthly resolution are used: (1) Climate Forecast System Reanalysis Versions 1 and 2 (CFSR; Saha et al., 2014) available at 0.5° horizontal resolution and spanning the period from January 1979 to August 2019. (2) European Centre for Medium-range Weather Forecast (ECMWF) Re-Analysis 5 (ERA5; Hersbach et al., 2020) available at 0.25° horizontal resolution for the period January 1979 to January 2020. (3) Ocean Reanalysis System Version 4 (ORA-S4; Balmaseda et al., 2013) from the ECMWF available at 1° horizontal resolution and spanning the period January 1958 to December 2017. Wind stress and sea level pressure (SLP) are taken from ERA5. The 20°C isotherm depth (z_{20}) is taken from ORA-S4.

2.1.2. Observations

Observational SST products used are (1) Hadley Centre Sea Ice and SST data set Version 1.1 (HadI-SST; Rayner et al., 2003) available at 1° horizontal resolution for the period January 1870 to December 2019. (2) Centennial in situ Observation-Based Estimates SST (COBE-SST; Ishii et al., 2005) available at 1° horizontal resolution and spanning the period January 1891 to December 2019. (3) Optimum Interpolation SST Version 2 (OI-SST; Reynolds et al., 2007) available at 0.25° horizontal resolution for the period September 1981 to December 2019. Table S1 in the supporting information provides an overview of the data sets and variables used.

2.2. Methods

In order to investigate the changes in the interannual SST variability in the ABA since 2000, we compare the periods January 1982 to December 1999 and January 2000 to December 2017. The year 2000 was chosen as the year of separation because major shifts occurred around this year both in the tropical Atlantic (Prigent et al., 2020) and tropical Pacific (Hu et al., 2013, 2017, 2020; Li et al., 2019; Lübbecke & McPhaden, 2014; McPhaden, 2012). All analyses use monthly-mean anomalies computed by subtracting the climatological monthly-mean seasonal cycle derived separately for each data set and period. Prior to all analyses, linear trends calculated over the entire period 1982–2017 were removed.

3. SST Variability

The magnitude of the interannual SST variability in the southeastern tropical Atlantic, as measured by the standard deviation, has undergone a strong multidecadal reduction (Figure 1a). The time series of the SST anomalies (SSTa) averaged over the ABA (Figure 1b) exhibits a clear change in character from the pre-2000 period to the post-2000 period. The seasonal cycle of the standard deviation of the SSTa in the ABA exhibits a distinct maximum in MAM (Figure 1c), when most of the Benguela Niños/Niñas occur (Imbol Koungue et al., 2017, 2019). However, the standard deviations during 2000–2017 are much smaller. There is still considerable interannual variability after 2000, but major events are fewer and SST fluctuations less persistent (Figure 1d).

While the MAM SST in the ABA has warmed by 0.3 K from 1982–1999 to 2000–2017 (Figure S1a), the meridional gradient of MAM SST in the ABA remained nearly constant (Figure S1b). Vizy et al. (2018) showed a poleward trend of the Angola-Benguela Frontal Zone (ABFZ), which could have influenced the ABA SST variability as the area of variability would shift with it. However, the observed reduction in SST variability occurred over a relatively large region. While the reduction is significant mainly to the north of the ABFZ, it extends almost along the whole Angolan and Namibian coasts (Figure 1a). Therefore, the reduction is not likely associated with a poleward displacement of the ABFZ.

The standard deviation of SSTa in the ABA calculated over all calendar months has weakened by 22.3%, from 0.74 ± 0.05 K in 1982–1999 to 0.58 ± 0.07 K in 2000–2017. Strongest reduction occurred in MAM

Table 1
Standard Deviation of the ABA-Averaged SSTa (K) for the Periods 1982–1999 and 2000–2017

| Product | 1982–1999 | | 2000–2017 | | Reduction (%) | |
|----------|-----------------|-----------------|-----------------|-----------------|----------------|--------------|
| | All month | MAM | All month | MAM | All month | MAM |
| CFSR | 0.75 | 1.15 | 0.64 | 0.83 | 15 | 28 |
| ERA5 | 0.75 | 1.10 | 0.56 | 0.80 | 25 | 27 |
| HadI-SST | 0.72 | 0.91 | 0.48 | 0.63 | 33 | 31 |
| COBE-SST | 0.64 | 0.90 | 0.48 | 0.58 | 25 | 36 |
| OI-SST | 0.78 | 1.23 | 0.66 | 0.84 | 16 | 32 |
| ORA-S4 | 0.78 | 1.18 | 0.63 | 0.84 | 20 | 29 |
| EM | 0.74 ± 0.05 | 1.08 ± 0.13 | 0.58 ± 0.07 | 0.75 ± 0.11 | 22.3 ± 6.2 | 30.5 ± 3 |

Note. EM denotes the ensemble mean of all products (Table S1).

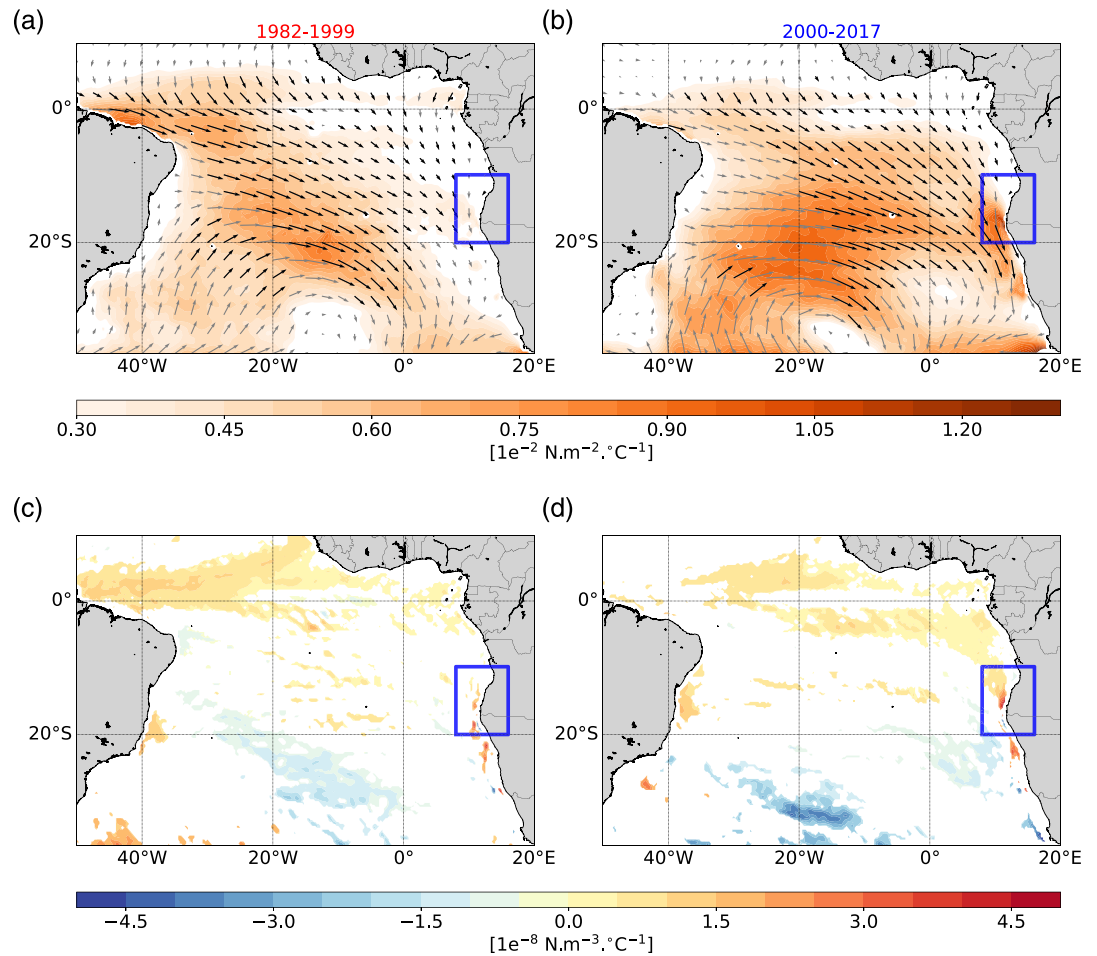


Figure 2. The vectors represent the regressions of detrended ERA5 wind stress anomalies on ERA5 ABA-averaged (8°E to the coast, 20–10°S; blue box) SSTa with winds leading by 1 month for (a) 1982–1999 and (b) 2000–2017. Regressions have been calculated for each wind stress component separately. The color shading depicts the magnitude of the vectors. Black (gray) arrows indicate pointwise significant (not significant) regressions for both components at the 95% level according to a Student's *t* test. (c, d) Regression coefficients of detrended ERA5 wind stress curl anomalies on ERA5 ABA-averaged SSTa with the wind stress curl anomalies leading by 1 month during 1982–1999 and 2000–2017, respectively. Displayed regressions are significant at the 95% level according to the Student's *t* test.

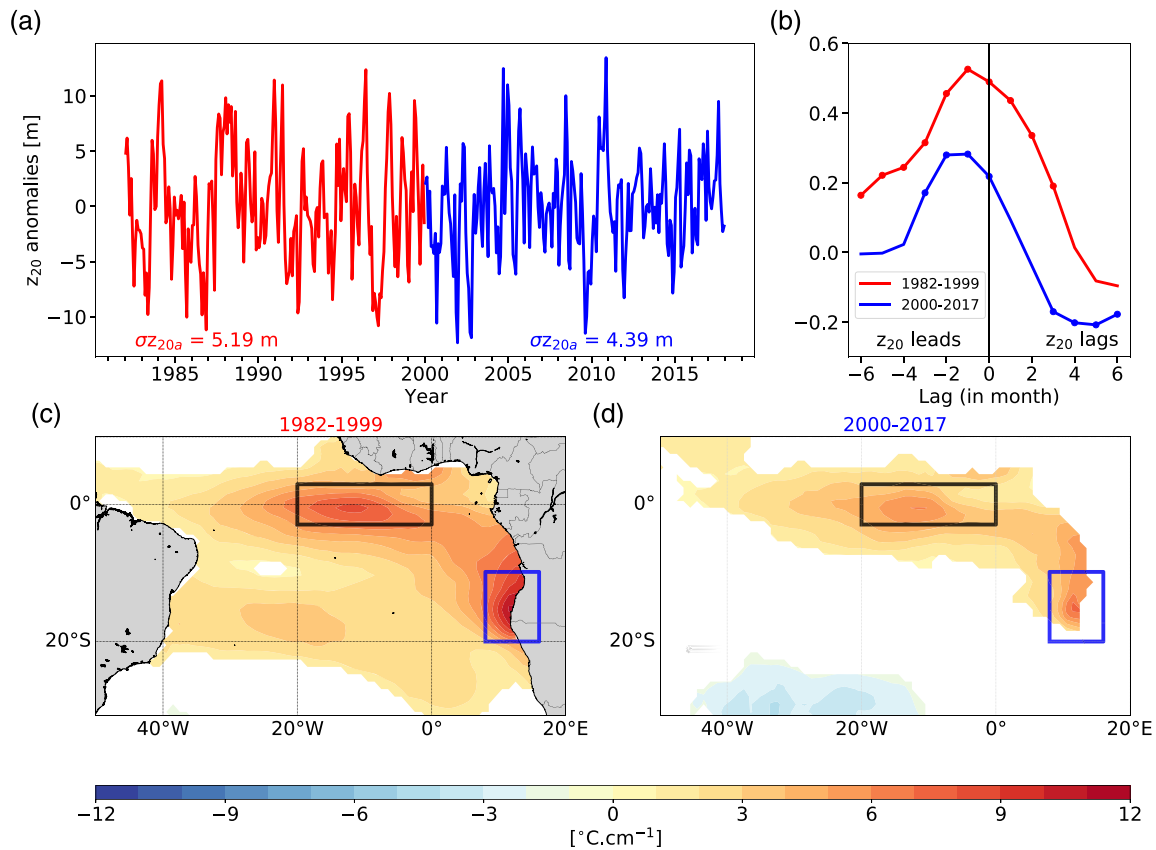


Figure 3. (a) Time series of monthly ATL3 ORA-S4 20°C isotherm depth anomalies (z_{20a}). (b) Cross correlation of monthly ATL3 z_{20a} and ABA SSTA for 1982–1999 (red) and 2000–2017 (blue). Dots indicate correlations that are significant at the 95% level. (c, d) Regression coefficients of the detrended ORA-S4 SSTA on ATL3 ORA-S4 z_{20a} with the z_{20a} leading by 1 month during (c) 1982–1999 and (d) 2000–2017. Only statistically significant regressions at the 95% level are shown. Statistical significance is assessed by the Student's t test.

(Table 1). The MAM standard deviation was 1.08 ± 0.13 K during 1982–1999 and decreased by 30.5% to 0.75 ± 0.11 K during 2000–2017 (Table 1).

4. Relative Roles of Equatorial and Local Forcing

During 1982–1999, the ABA SSTA are mainly linked to zonal wind stress fluctuations in the western equatorial Atlantic, as shown by linear regression on ABA SSTA (Figures 2a and S2a). Equatorial zonal wind stress fluctuations can generate EKW that propagate eastward along the equator. At the West African coast, part of the EKW energy is transmitted poleward as CTWs which can trigger coastal warm/cold events (Bachelery et al., 2019; Florenchie et al., 2003, 2004; Illig et al., 2004; Imbol Kougue et al., 2017, 2019; Lübbecke et al., 2010). In contrast, during 2000–2017 (Figures 2b and S2b), the link between western equatorial zonal wind stress fluctuations and coastal SSTA is considerably weaker, which is consistent with the reduced equatorial wind stress variability described in Prigent et al. (2020). Instead, relatively large regression coefficients are found in the southeastern tropical Atlantic close to the West African coast (Figure 2b), suggesting that the role of local meridional wind stress fluctuations in driving interannual SST variability in the ABA has increased. This is further supported by the strengthened link between ABA SSTA and near-coastal wind stress curl anomalies along the Angolan and Namibian coasts when comparing 1982–1999 (Figure 2c) to 2000–2017 (Figure 2d). We also observe a magnitude maximum of the regression coefficients around 20°S and 20°W (Figure 2b), which, however, is not statistically significant at 95% according to a Student's t test.

We next examine the impact of the equatorial zonal wind stress on thermocline depth. Variability in the latter serves here to assess the role of EKW activity (Imbol Kougue et al., 2017).

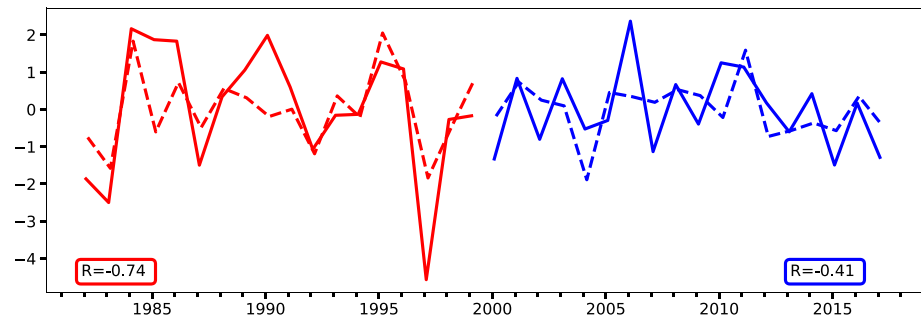


Figure 4. Time series of interannual anomalies of February SAA index (SLP (hPa) averaged over 40°S to 20°S and 30°W to 10°W; inverted, full line) and March ABA SST (°C, dashed line) from ERA5 during 1982–1999 (red) and 2000–2017 (blue).

The standard deviation of the thermocline depth anomalies (z_{20a}) in the ATL3 box (20°W to 0°, 3°N to 3°S; Figure 3a) has reduced by 15.4% from 5.19 m during 1982–1999 to 4.39 m during 2000–2017. Further, the relationship between ATL3 z_{20a} and ABA SSTa also has markedly weakened after 2000 (Figure 3b). In fact, during 1982–1999, the ATL3 z_{20a} was leading ABA SSTa by 1 month with a correlation of 0.52 whereas the correlation at the same lead time dropped to 0.28 during 2000–2017. These results suggest that after 2000 the importance of remote equatorial forcing of ABA SSTa by EKWs has substantially reduced. Consistent with this, the major warm event of 2016 resulted from a combination of different local processes (Lübbecke et al., 2019). The results shown in Figure 3b also imply that an index based on equatorial Atlantic oceanic variability has become a less skillful predictor for the ABA SST variability after 2000: While the shape of the cross-correlation function remained unchanged, the magnitude of the correlations has dropped considerably.

The link between the ABA SSTa and the equatorial ocean dynamics can be estimated by regressing the SSTa on the (detrended) ATL3 z_{20a} taken 1 month earlier. This link has weakened at the equator from 1982–1999 (Figure 3c) to 2000–2017 (Figure 3d), especially between 20°W and 5°E and along the West African coast between 5°S and 20°S. This again suggests that after 2000, equatorial thermocline displacement anomalies have less impact on the ABA SSTs. However, reanalysis products are known to exhibit large biases in the tropical Atlantic region (Huang et al., 2007; Kumar & Hu, 2012; Tchpalanga et al., 2018). High-resolution ocean models forced by the history of observed wind stress could be a way out of this dilemma.

Lübbecke et al. (2010) showed that western equatorial Atlantic zonal wind stress variations are linked to the variations of the strength of the SAA. Later, Lübbecke et al. (2014) demonstrated that this link is facilitated through the wind power. Richter et al. (2010) also highlighted the importance of the SAA on the development of warm events off the Angolan and Namibian coasts.

In agreement with Lübbecke et al. (2010), the fluctuations of the strength of the SAA in austral summer during 1982–1999 have been well anticorrelated with the subsequent austral fall ABA SSTs with a correlation coefficient of -0.74 (Figure 4). However, over the period 2000–2017, the correlation coefficient dropped to -0.41 . No major shift in the SAA position was found that could explain the diminishing correlation between March ABA SSTa and February SLP anomalies (SLPa) from 1982–1999 (Figure S3a) to 2000–2017 (Figure S3b). Moreover, since 2000 a weaker relationship between the SLP-anomaly field and ABA SSTa is evident in the regression maps (Figures S3c and S3d). Hence, the ABA SSTs during 2000–2017 are less influenced by the variations in the strength of the SAA than during 1982–1999. The reason for this weaker relationship is unclear and beyond the scope of this paper.

5. Discussion and Conclusions

This study documents a multidecadal reduction in the interannual SST variability in the ABA during 2000–2017 relative to 1982–1999. The interannual SST variability in the ABA has reduced in the annual mean by 22.3% during 2000–2017 relative to 1982–1999, with the strongest reduction amounting to 30.5% in MAM. The reduced interannual SST variability in the ABA goes along with a smaller influence of remote forcing by equatorial wind stress variability. The zonal wind stress variability over the western equatorial

Atlantic diminished during the recent decades, as reported by Prigent et al. (2020). Lower zonal wind stress variability tends to reduce EKW activity that is an important driver of SST in the ABA. This by itself enhances the relative importance of the local atmospheric forcing through near-coastal meridional wind stress and wind stress curl, if the local factors remain unchanged. However, the quantification of the relative importance of the local and remote wind stress forcing over the last decades remains a challenge due to limited data. Ocean modeling would be an alternative and additionally allow disentangling the contribution of each equatorial baroclinic mode to ABA SST variability.

Another factor that could have contributed to the reduced interannual SST variability in the ABA is the multi-decadal surface warming in the region. In MAM, the season of the largest interannual SST variability, the SST in the ABA has warmed by 0.3 K when comparing the pre-2000 period to the post-2000 period. This is consistent with Vizzy and Cook (2016) who investigated multidecadal changes in the southeastern tropical Atlantic over the period 1982–2013 and found significant SST warming trends along the Angolan/Namibian coasts of 0.5–1.5 K per 32 years. This multidecadal surface warming was associated with an increased net heat flux from the atmosphere and reduced coastal upwelling. The surface warming and concurrent subsurface cooling (Figures S4a and S4b) might have reduced surface-subsurface coupling in the post-2000 period. There is a shoaling of the stratification maximum in the ABA since 2000 (Figure S4b), which would support a larger sensitivity of the mixed layer to local forcing. Due to large biases in reanalysis products and limited observations (Huang et al., 2007; Kumar & Hu, 2012; Tchupalanga et al., 2018), large uncertainties remain regarding the potential influence of multidecadal changes in stratification on the interannual SST variability in the ABA.

Although some major remotely forced Benguela Niño/Niña events occurred after 2000, Tables S1 and S2 from Imbol Koungue et al. (2019) indicate a smaller number relative to previous decades. Over the period 1982–2015, out of eight (six) warm (cold) events only two (one) took place after 2000. However, over the same time period, out of 15 (7) moderate warm (cold) events 7 (5) occurred between 2000 and 2015. This illustrates that relative to 1982–1999, since 2000 fewer remotely forced major and more moderate events occurred in the ABA.

Numerous other potential factors could have contributed to the reduced SST variability in the ABA. One of them might be the interdecadal shift of El Niño/Southern Oscillation (ENSO) that occurred around 2000 (Hu et al., 2013, 2017, 2020; Lübbecke & McPhaden, 2014; McPhaden, 2012). This shift featured a decrease in ENSO variability, an increase in ENSO frequency (Hu et al., 2013, 2020) as well as a profound westward shift of the Walker Circulation in the equatorial Pacific (Li et al., 2019). The latter might have altered ENSO teleconnections, and thus, could have contributed to the weakened SST variability in the tropical Atlantic. However, the influence of the multidecadal shift in ENSO on the tropical Atlantic SST requires further analyses.

Finally, our results may have implications for the predictability of Benguela Niño/Niña events. In particular, the strong link between equatorial thermocline displacements and ABA SSTa during 1982–1999 has significantly weakened since 2000. In addition, we show that the strong link between the fluctuations in SAA strength and ABA SSTa observed during the pre-2000 period (Lübbecke et al., 2010) has diminished considerably during the post-2000 period. This raises the question as to whether predictors based on equatorial variables or the SAA strength are still useful to forecast Benguela Niño/Niña events.

Data Availability Statement

The surface and ocean profile data sets were taken from the following publicly available sources: OI-SST (<https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>), ORA-S4 (<http://icdc.cen.uni-hamburg.de/projekte/easy-init/easy-init-ocean.html>), ERA5 (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>), HadI-SST (<https://www.metoffice.gov.uk/hadobs/hadisst/>), COBE-SST (<https://psl.noaa.gov/data/gridded/data.cobe2.html>), and CFSR (<https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr>).

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