1. Introduction

The Benguela Current in the South Atlantic is one of the four major regions of upwelling in the world associated with the eastern boundary currents, analogous to its counterparts, the California Current in the North Pacific, Humboldt Current in the South Pacific, and Canary Current in the North Atlantic. These regions are home to great biological diversity. They are among the most productive areas in the oceans due to their position in relation to the trade winds that favors the upwelling of cold subsurface waters rich in nutrients to the euphotic zone. Consequently, sea surface temperatures (SSTs) are a good indicator of the upwelling strength which is related to the health of the marine ecosystem and the fisheries of the Benguela upwelling (Hutchings et al. 2009; Veitch et al. 2009, Mead et al. 2013; Blamey et al. 2015). The Benguela Current is flanked by warm waters from the Agulhas Current to the south and by the tropical water of the Angolan coast to the north. Changes in SST patterns and values are a good indication of the change in upwelling intensity due to change in wind speed and direction. Therefore, changes in SST can have consequences for the marine ecosystem and fisheries in the Benguela upwelling.

The Benguela is under the influence of the South Atlantic anticyclone, which generates the upwelling favorable southeasterly wind (Fig. 1). Transient cyclonic low pressure systems suppress upwelling and increase SST. In the southern Benguela, from about 30° to 35°S, the southeasterly winds strengthen during austral summer when the South Atlantic anticyclone and midlatitude low pressure system shift poleward, enhancing upwelling. From April to September, in the southern Benguela, winds are mostly northwesterly and southwesterly, which are not favorable for upwelling. This is because of the influence of transient eastward-moving midlatitude cyclonic low pressure systems, mostly cold fronts, that generate wind of opposite direction to the southeasterly upwelling favorable winds created by the South Atlantic anticyclone. The central Benguela, at 25°–30°S, experiences strong upwelling favorable wind all year long, albeit with a maximum in austral summer. Even though the northern Benguela between 17° and 25°S is a region of perennial upwelling, it experiences stronger upwelling and favorable winds in austral autumn and winter (Hutchings et al. 2009).

The northern Benguela region is bordered to the north by the Angola–Benguela Front. It is also influenced by equatorial remote winds variation that can generate persistent SST anomalies in austral summer and fall via ocean dynamics. These SST anomalies are produced by the Benguela Niños and Niñas (Shannon et al. 1986; Florenchie et al. 2004; Rouault et al. 2007, 2018; Lübbecke et al. 2010; Imbol Koungue et al. 2017, 2019). Benguela Niños are characterized by persistent warmer-than-normal SST in Angola and northern Namibia and vice versa for Benguela Niñas. They are generally caused by changes in the winds along the western equatorial Atlantic, triggering Kelvin waves that propagate

**Impact of El Niño–Southern Oscillation on the Benguela Upwelling**

M. Rouault and F. S. Tomety

* Nansen Tutu Center for Marine Environmental Research, Department of Oceanography, University of Cape Town, Cape Town, South Africa

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ABSTRACT: The impact of El Niño–Southern Oscillation (ENSO) on the southern African climate is well documented and provides skill in the seasonal forecast of rainfall, but less is known about the impact of ENSO on the Benguela Current west of southern Africa. There is a significant weak correlation between ENSO and the Benguela Current upwelling sea surface temperature (SST) in austral summer. Correlation is positive for southern Benguela and negative for northern Benguela. A significant correlation exists with up to 8 months lag when ENSO leads. The impact of ENSO is due to weaker-than-normal upwelling favorable southeasterly winds during El Niño in southern Benguela, leading to warmer-than-normal coastal SST. In contrast, during La Niña, stronger-than-normal southeasterly winds lead to cooler-than-normal SST. The opposite effect applies to northern Benguela. The coastal wind change is part of an ENSO large-scale basinwide perturbation in the tropical and South Atlantic. However, non-ENSO-related SST variation in the Benguela upwelling can be as important as ENSO-related SST perturbation, and some ENSO events do not lead to the expected changes. Changes in the Benguela upwelling are linked to changes in the intensity of the trade winds associated with a change of the South Atlantic anticyclone intensity and position. In southern Benguela, changes are also associated with variations in midlatitude low pressure systems and associated upwelling unfavorable westerly winds. La Niñas favor the development of Benguela Niños in Angola and Namibia. This study shows the potential for SST seasonal predictability in the Benguela upwelling due to the leading lag correlation between ENSO and the Benguela upwelling SST.

KEYWORDS: South Atlantic Ocean; El Niño; Teleconnections; Upwelling/downwelling

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Corresponding author: Mathieu Rouault, mathieu.rouault@uct.ac.za

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along the equator up to the African coast, where they turn into poleward coastal trapped waves. These waves change the mixed layer depth and generate downwelling facilitating the development of warm SST anomalies in the Angola and Benguela region (Ostrowski et al. 2009; Bachélery et al. 2020; Imbol Koungue et al. 2019). Benguela Niños also increase warm tropical water inflow into northern Benguela across the Angola–Benguela Front while Benguela Niñas reduce it (Hutchings et al. 2009; Rouault 2012; Imbol Koungue et al. 2017, 2019).

Local changes in the winds that can lead to interannual variability in the Benguela upwelling have been linked to El Niño–Southern Oscillation (ENSO) in only a handful of studies. Rouault et al. (2010) were the first to document the impact of ENSO on the South African coastline from 1982 to 2009. La Niña austral summers were associated with stronger upwelling favorable southeasterly winds and colder-than-normal coastal SST at the west and south coast of South Africa. In comparison, El Niño weakened the upwelling favorable southeasterly winds leading to less upwelling and warmer-than-normal coastal SST. This wind variability resulted from latitudinal shifts in the South Atlantic anticyclone (Dufois and Rouault 2012). The relation between SST and ENSO in northern Benguela is less documented. It is the opposite in southern Benguela, which was also attributed to a shift in the South Atlantic anticyclone during ENSO (Blamey et al. 2015). Other studies reported a moderate correlation between ENSO and changes in the southern Benguela only (Tim et al. 2015), the Agulhas Bank only (García-Reyes et al. 2018), or the 850 hPa wind speed in the interior of southern Africa (Nchaba et al. 2017). Most recently, Duncan et al. (2019) have linked La Niña events to intense upwelling events along the south coast of South Africa. Based on these studies, the ENSO impact in the Benguela Current is inconsistently reported. Using SST and vertical velocity derived from an ocean model as well as reanalyzed NCEP wind speed, Tim et al. (2015) found a weak significant correlation with ENSO and northern Benguela upwelling only in austral fall (March–May) and for southern Benguela in summer (December–February) and fall. Rouault et al. (2010) only investigated the South African coastline SST, which includes the southern Benguela, and the regional atmospheric forcing. Dufois and Rouault (2012) using high-resolution satellite remote sensing derived SST and measured wind speed, researched the impact of ENSO on False Bay, Cape Town, an embayment in the southern Benguela not directly subjected to upwelling. Blamey et al. (2015) was a review paper presenting only a summer El Niño and La Niña SST composite from 1982 to 2010, showing a weak impact of ENSO in the northern Benguela. García-Reyes et al. (2018), using sea level pressure and an upwelling intensity derived index calculated with wind speed from reanalyzed climate dataset NCEP-2, did not find a correlation between ENSO and the Benguela upwelling SST, but they did find one for the Agulhas Bank, south of Africa. Nchaba et al. (2017) found a weak correlation between 850-hPa wind and ENSO inland in South Africa but not along the Benguela Current. No lag correlation or systematic correlation for each individual month of summer was calculated in those studies. Moreover, Colberg et al. (2004), in their study of the impact of ENSO on the South Atlantic, omitted the Benguela in their domain study. Although several studies have reported the impact of ENSO on the South Atlantic or the South Atlantic anticyclone and the midlatitude atmospheric circulation, they did not evaluate the effect of ENSO on the Benguela Current explicitly (Mo and Paegle 2001; Sun et al. 2017; Puaud et al. 2017; Rodrigues et al. 2015). On the other hand, studies looking at mechanisms linking the Pacific and the Indian Ocean to southern African inland climate, especially rainfall, are numerous. The improvement in our capability of predicting rainfall variability over land in austral
summer at the seasonal scale is mostly due to the impact of ENSO (Landman et al. 2019). Many studies have shown that climate and rainfall variability in southern Africa is significantly influenced by ENSO in austral summer, but the impact on coastal SST is not mentioned in the rainfall studies. El Niños are generally, but not always, associated with droughts over southern Africa and La Niñas with above-average rainfall (Fauchereau et al. 2003; Rouault and Richard 2005; Pohl et al. 2010; Créat et al. 2012; Dieppois et al. 2019, among others). The predictability of rainfall variability over southern Africa, therefore, come from the fact that ENSO influence on rainfall peaks in austral summer (Landman and Mason 2001; Landman et al. 2019). Austral summer is also the main upwelling seasons. Seasonal rainfall forecasting skill results from atmospheric models’ ability to capture the influence of the ENSO events over the region (Johnston et al. 2004; Landman et al. 2019). For many years, this relationship has been exploited operationally by weather services in southern Africa to predict seasonal rainfall and the occurrence of droughts at the seasonal scale.

The main goal of this study is to determine more consistently the impact of ENSO on the coastal SST of the Benguela upwelling system. We also look at the impact of other modes of climate variability that have been related to the southern African climate in the literature. We also investigate the lead–lag relationships between ENSO and local SST for the period of 1982–2020. The results include lag correlation analysis between the ENSO index and SST anomaly time series for the northern and southern Benguela. El Niño and La Niña composites of SST, surface wind, sea level pressure, geopotential height, and wind at various atmospheric levels are calculated to understand the mechanism linking ENSO to the Benguela and the South Atlantic in a unifying way. Results are described in section 3. Sections 4 and 5 present, respectively, a discussion and conclusions.

2. Data and methods

We use monthly SST obtained from the NOAA Optimum Interpolation SST (OISST) version 2 dataset (Reynolds et al. 2002) with a resolution of 1° × 1° for 1982–2020. We split the domain along the coast of southern Africa into two segments of the same size, 5° latitude long × 1° longitude wide (Fig. 2). The northern domain is called northern Benguela, and the southern domain is called southern Benguela, and they are plotted in red in Fig. 2 together with the mean 1982–2020 January SST.

The OISST dataset is also used to calculate the Niño-3.4 index. The Niño-3.4 index is obtained by averaging the monthly SST anomaly within the box 5°S–5°N and 170°–120°W. OISST is also used to calculate the Atlantic Niño-3 index (ATL3), the South Atlantic subtropical dipole index (SASD), and the subtropical Indian Ocean dipole index (SIOD), whose domains are plotted in Fig. 3. The Niño-3.4 index is obtained by averaging the monthly SST anomaly within the box 5°S–5°N and 170°–120°W and the ATL3 index within the box 3°S–3°N and 20°W–0°. The SASD index is obtained by subtracting the SST anomalies averaged within the southern pole (20°W–0°, 25°–15°S) from the northern pole (30°W–0°, 40°–30°S) following Moricka et al. (2011) while the SIOD index is the difference between the SST anomalies averaged within 55°–65°E, 37°–27°S and 90°–100°E, 28°–18°S, following Behera and Yamagata (2001). We also use the oceanic Niño index (ONI) provided by the Climate Prediction Center. The Antarctic Annular Oscillation index (AAO) is also obtained from the Climate Prediction Center and is defined as the first leading mode from the EOF analysis of monthly mean height anomalies at 700 hPa and is obtained at https://www.cpc.ncep.noaa.gov.

For the atmospheric variables, we use monthly data obtained from the new ECMWF ERA5 reanalysis with a resolution of about 30 km × 30 km for the period 1982–2020 (Hersbach et al. 2020). We use sea level pressure (SLP), surface wind speed at 10 m, and wind and geopotential height at the 1000-, 850-, 700-, and 500-hPa levels. For all datasets, monthly anomalies are estimated by subtracting the monthly climatological mean after removing a linear trend obtained from the least squares fit. Normalized SST anomalies are obtained by dividing the SST anomalies by their standard deviation. We use detrended normalized SST anomaly and ONI time series for all correlation and composites analyses.

Composites are calculated for the average of November–January (NDJ) and February–April (FMA) for El Niño and La Niña years. We have selected the following 13 La Niña events according to ONI: 1983/84, 1984/85, 1988/89, 1995/96,

3. Results
   a. Preliminary results

   The summer (December–March) climatology for 1982–2020 of SLP and surface wind speed and direction (Fig. 1) shows that the position of the South Atlantic anticyclone leads to strong southeasterly winds along the coast of southern Africa. To the south of the South Atlantic anticyclone lies the westerly wind associated with the southern extension of the South Atlantic anticyclone and the midlatitude cyclonic low pressure systems. The northern part of a temperate cyclonic low pressure system, mostly cold fronts, can easily reach 30°S at the surface even in summer, suppressing upwelling along the coast of southern Africa. Figure 1 is the reference upon which anomalies in the wind and SLP will be discussed. The corresponding mean 1982–2020 wind speed and OISST is shown in Figs. S1 and S2 in the online supplemental material. Note that

   ![Fig. 3. NDJ correlation between regional SST anomalies and (a) northern Benguela and (b) southern Benguela. (c),(d), As in (a) and (b), but for FMA. Also plotted are the ATL3 index domain (north blue box) and the SASD index domains (black middle and south boxes).](image-url)
Table 1. NDJ synchronous cross correlation between northern Benguela (NB), southern Benguela (SB), ONI, ATL3, SASD, SIOD, and AAO. In bold are correlations significant at the 95% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>NB</th>
<th>SB</th>
<th>ONI</th>
<th>ATL3</th>
<th>SASD</th>
<th>SIOD</th>
<th>AAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>1</td>
<td>0.31</td>
<td>0.26</td>
<td>0.19</td>
<td>−0.13</td>
<td>0.06</td>
<td>−0.05</td>
</tr>
<tr>
<td>SB</td>
<td>1</td>
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<td>0.03</td>
<td>−0.15</td>
<td>−0.10</td>
<td>0.09</td>
<td></td>
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<tr>
<td>ONI</td>
<td>1</td>
<td>0.47</td>
<td>−0.59</td>
<td>−0.32</td>
<td>−0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATL3</td>
<td>1</td>
<td>−0.18</td>
<td>0.76</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SASD</td>
<td>1</td>
<td>0.29</td>
<td>−0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIOD</td>
<td>1</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. FMA synchronous cross correlation between northern Benguela (NB), southern Benguela (SB), ONI, ATL3, SASD, SIOD, and AAO. In bold are correlations significant at the 95% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>NB</th>
<th>SB</th>
<th>ONI</th>
<th>ATL3</th>
<th>SASD</th>
<th>SIOD</th>
<th>AAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
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<td>−0.17</td>
<td>0.47</td>
<td>0.46</td>
<td>0.40</td>
<td>−0.48</td>
<td>−0.38</td>
</tr>
<tr>
<td>SB</td>
<td>1</td>
<td>0.45</td>
<td>−0.11</td>
<td>−0.34</td>
<td>−0.11</td>
<td>−0.24</td>
<td></td>
</tr>
<tr>
<td>ONI</td>
<td>1</td>
<td>0.47</td>
<td>−0.26</td>
<td>−0.36</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATL3</td>
<td>1</td>
<td>−0.41</td>
<td>−0.79</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SASD</td>
<td>1</td>
<td>0.57</td>
<td></td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIOD</td>
<td>1</td>
<td>0.16</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The correlation between ONI and regional SST suggests that the impact of ENSO on the Benguela upwelling is part of a large-scale basinwide effect of ENSO on the South Atlantic. The correlation between ENSO and SST is especially significant in the midlatitude where westerly winds are dominant for both seasons. For both seasons but with different values of correlation, spatial extent, and degree of significance, we observe a positive correlation between ENSO and southern Benguela of up to 0.5 in FMA (Fig. 4b). Correlation with the offshore region of the South Atlantic is stronger in NDF (Fig. 4a), while correlation in the Benguela upwelling is stronger in FMA (Fig. 4b). During El Niño, the southern Benguela is warmer than normal. This area of positive correlation in southern Benguela is part of a larger region of positive correlation occupying most of the South Atlantic from 40°W to 10°E and from 15° to 30°S. A large region of higher negative correlation of up to 0.8 occurs in both seasons to the south. The positive correlation between ONI and basinwide SST is higher in early summer than in late summer in the middle of the South Atlantic. In contrast, the correlation is higher in late summer within the Benguela upwelling system. In the northern Benguela, the correlation is negative and extends to the northwest and is collocated with the northern region of the South Atlantic anticyclone (Fig. 1). Based on those correlations, we extract two time series, one for the northern Benguela and the other for the southern Benguela, averaged in the red domains shown in Fig. 2 and described in section 2.

Monthly lagged correlations between ONI and monthly northern and southern Benguela SST anomalies are presented in Fig. 5. Significant correlations at the 95% confidence level are marked by a star and are roughly above 0.3. The months are plotted on the abscissa from July to June of the following year to focus on the upwelling season. On the ordinate, −1 corresponds to ONI leading northern or southern Benguela by 1 month. Figure 5a shows that significant correlations of up to −0.45 for northern Benguela during January to May with up to 6 months of lag (Fig. 5a). Correlations for southern Benguela (Fig. 5b) are lower in absolute values than those for northern Benguela but start earlier in the season and are significant with up to 4 months lags only.
Correlation is higher at the end of the upwelling season in late summer (FMA) for both domains.

A comparison of the two time series of SST anomalies for northern Benguela and southern Benguela in FMA plotted with the FMA ONI is presented in the top and bottom panels of Fig. 6, respectively. El Niño years are in red, and La Niña years are in blue. The list of La Niña and El Niño years is found in section 2. Figure 6 shows the complexity of the relation between ENSO and coastal SST in the Benguela regions. A closer look at the relationship between northern and southern Benguela and ENSO shows that warm anomalies superior to 0.5 standard deviations in the northern Benguela (Fig. 6a) occur mainly during La Niña but also during neutral and El Niño years as well. Out of 11 warm events in the northern Benguela, 8 occur during La Niña, 1 occurs during El Niño, and 2 occur during neutral years. Cold events occur predominantly during El Niño and neutral years in northern Benguela. Out of 11 cold events, 6 events occur during El Niño and 5 during neutral years (Fig. 6a). For southern Benguela (Fig. 6b), out of 8 warm events, 5 occur during El Niño years and 3 during neutral years. Cold events inferior to −0.5 standard deviation occur predominantly during neutral (5) and La Niña years (6) and none during El Niño years in southern Benguela.

Therefore, not all El Niños lead to warm events and not all La Niñas to cold events in southern Benguela. Moreover, there is no robust relationship between the strength of the ENSO events and the amplitude of the SST anomalies. For instance, the strongest El Niños on record, 1982/83 and 1997/98, are not followed by the strongest events in either the northern Benguela or southern Benguela. However, El Niño and La Niña events usually start well before austral summer and, in general, mature and peak in austral summer, giving ample warning for forecasting SST in the region. As previously seen for the northern Benguela, the correlation between SST and ONI is negative in FMA. However, Fig. 6 also reveals that one of the strongest Benguela Niño events occurred during the 1995 El Niño. Well-documented Benguela Niño events occurred in FMA in La Niña years in 1984, 1996, 1999, 2001, and 2011. The association between La Niña and Benguela Niños is reported here for the first time. On the other hand, 4 out of 7 of northern Benguela Niños occur during El Niño years. At last, the 1995 event shows that canonical Benguela

![Fig. 4. Correlation between ONI and regional SST detrended anomalies in (a) early summer (NDJ) and (b) late summer. Significant correlations at the 95% confidence level are marked with a dot.](image)

![Fig. 5. Lag Spearman correlation between ONI and monthly (a) northern Benguela and (b) southern Benguela SST anomalies. Significant correlations at a 95% confidence level are marked with a star and roughly below 0.3 and above 0.3; on the abscissa is plotted the month from July to June of the following year and on the ordinate the lag −1 corresponds to ONI leading northern or southern Benguela by 1 month.](image)
Niños and Niñas can happen independently of ENSO events. Removing the 1995 event from the SSTs increases the correlation between ENSO and northern Benguela from $-0.45$ to $-0.7$ in FMA.

c. Atmospheric forcing of ENSO

To understand the impact of ENSO on the Benguela region in the context of the South Atlantic and the mechanisms leading to the coastal anomalies in NDJ, Fig. 7 shows NDJ SST composite anomaly (top) and surface wind speed and direction composite anomaly (bottom) for El Niño years (left) and La Niña years (right). Figures 4 and 7 imply that during ENSO, Benguela SST anomalies are created by a large-scale atmospheric disturbance that impacts all of the South Atlantic and the Atlantic sector of the Southern Ocean with higher impact offshore than at the southern African coast in early summer (NDJ). The NDJ El Niño and La Niña SST composite significant areas (dotted regions in the top panels of Fig. 7) are similar to the correlation map presented in Fig. 4 but with more spatial extension. The composite of SST anomalies for El Niño events (Fig. 7a) shows an east-to-west large band of positive SST anomalies extending west of southern Africa to Brazil. South of this band lies a domain of negative SST anomalies of opposite sign to southern Benguela SST. There is a small effect of El Niño on the African coast in NDJ (Figs. 4a, 7a and Table 1). South of Africa, the SST anomalies are negative during El Niño. The La Niña composite SST anomalies (Fig. 7b) are nearly the opposite but with weaker and less significant anomalies. The NDJ El Niño surface wind composite anomalies (Fig. 7c) seem well collocated with the El Niño SST composite anomalies. Negative northwesterly wind anomalies, meaning weaker-than-normal southeasterly wind speed, occur from southern Africa to the east of Brazil in a similar region as the El Niño SST positive anomalies. South of the band of negative northwesterly anomalies lies a region of positive southwesterly, westerly, and northwesterly wind speed anomalies, meaning that during El Niño, stronger wind speed than normal occurs in the midlatitudes where the El Niño SST anomalies are mostly negative, suggesting a direct effect of wind change on SST change. Stronger southeasterly winds are found along northern Namibia during El Niño, where there is a small nonsignificant cooling in the Benguela upwelling (Fig. 7a). There are weaker easterly trade winds south of the equator in the tropical Atlantic during El Niño and stronger easterly trade winds during La Niña. Along the equator toward Brazil from 50° to 30°W, in a key region for the development of Benguela Niño and Niñas, the easterly winds are stronger during El Niño (Fig. 7c) and weaker during La Niña (Fig. 7d). Stronger southerly and southeasterly upwelling favorable wind in the Benguela upwelling leads to stronger upwelling and colder SST. The reverse is also true. El Niño wind composite (Fig. 7c) explains the SST composite pattern (Fig. 7a) at the coast and for large areas of the open ocean. Mechanisms by which local changes in the wind speed bring about SST anomalies in the open ocean South Atlantic have been previously reported for this region during ENSO or other phenomena such as the South Atlantic subtropical dipole and will be put forward and discussed later (Colberg et al. 2004; Morioka et al. 2011; Rodrigues et al. 2015; Santis et al. 2020). The La Niña SST and wind composites (Figs. 7c,d) are nearly opposite to the El Niño SST and wind composites.
(Figs. 7a,b) but with stronger wind speed anomalies in absolute value south of 30°S and slightly different spatial extent of the positive or negative anomalies.

Next, to understand the causes of the basinwide and coastal wind change during El Niño and La Niña in NDJ, we calculate the El Niño and La Niña composites of SLP anomalies, and we superimpose the same surface wind speed, and direction anomalies for El Niño and La Niña calculated for Figs. 7c and 7d in Figs. 8a and 8d, respectively.

The stronger wind anomalies occur in the region where the pressure gradient changes the most, visible from Brazil to southern Africa in a northeast to a southwest band of collocated SLP gradient anomalies and northwesterly wind anomalies. That band brushes off the coast of South Africa. As wind speed is a function of the pressure gradient, the change in pressure gradient during El Niño explains the change in wind speed from Brazil to southern Africa. Additionally, for El Niño (Fig. 8a) a low-pressure anomaly is also present in the midlatitude anchored at about 50°S, 0°, leading to westerly wind anomalies. The surface low-pressure and high-pressure anomalies can be traced back in all layers of the troposphere at 850, 700, 500 (not shown), and 200 hPa (Fig. 9).

Additionally, the increase in wind speed off northern Namibia during El Niño (Fig. 7c) extending toward Brazil is linked to higher-than-normal pressure anomalies and also strengthening of the pressure gradient from southwest to northeast direction. This is also coherent with the El Niño teleconnection pattern (Fig. 9). Change in the high pressure system and low pressure system during ENSO leads to the change in pressure gradient and intensity leading to the associated change in wind speed and SST. Otherwise, average ERA5 SLP composites during El Niño, La Niña, and neutral years (Fig. S3) suggest that the South Atlantic anticyclone is shifted to the south by a few degrees during La Niña and by a few degrees north and to the east during El Niño. This shift explains the southeasterly wind anomalies in the southern Benguela and the northwesterly and westerly wind anomalies in northern Benguela during La Niña and the opposite effect during El Niño. However, during La Niña (Fig. 8b and Fig. S3b), in the midlatitude, the increase in pressure is not totally due to the shift in the South Atlantic anticyclone, which is a few degrees only, but higher-than-normal widespread midlatitude seal level pressure. The association between the anomaly of SLP and wind speed during La Niña and El Niño shows that the atmospheric impact of ENSO on the South Atlantic is basinwide and that the Benguela Current lies to the east and northeast of the regions of the highest impact in NDJ.

Next, we are looking at El Niño and La Niña composite in FMA because the correlation between ENSO and the Benguela Current SST is higher in late summer (Figs. 4 and 5). We want to know if the atmospheric conditions are different between early and late summer, which could explain the correlation

![Fig. 7](image_url)

**Fig. 7.** (top) NDJ SST anomalies composite for (a) El Niño and (b) La Niña. (bottom) NDJ surface wind speed (color) and direction (arrows) anomalies composite for (c) El Niño and (d) La Niña from 1982 to 2020. Significant composite anomalies at 95% confidence level are marked with dots for SST and gray arrows for wind speed using the Student’s t test.
difference or if the highest correlation in FMA is due to the persistence of the ENSO impact during all summer. There is also a lack of correlation at the monthly scale in midsummer (Fig. 5). Figures 10–12 represent the same calculations done for Figs. 7–9 but for late summer (FMA).

At the coast, the FMA composites of SST anomalies for El Niño and La Niña events (top panels in Fig. 10) share some of the spatial features of the ENSO correlation pattern shown previously in Fig. 4, namely, two large domains of correlation and anticorrelation extending from South Africa to Brazil and in the low latitudes, respectively, quite similar as for NDJ (Figs. 7a,b). SST anomalies in southern Benguela and northern Benguela are of opposite signs and are most significant for La Niña composites (Figs. 10a,b). The El Niño FMA surface wind composite (bottom-left panel in Fig. 10) seems to be well collocated with the El Niño FMA SST composite (Fig. 10a). During El Niño, weaker-than-normal wind speed occurs from South Africa to Brazil, with stronger-than-normal wind speed in the midlatitudes collocated with the midlatitude cooling (Fig. 10c). During El Niño, higher-than-normal winds are found along northern Namibia, consistent with stronger upwelling and colder SST (Figs. 10a,c). Turning our attention to northern Benguela, the main difference from the NDJ SST composite is that northern Benguela is anticorrelated to the southern part of the southern Benguela domain and the south coast of South Africa, especially during La Niña. As is the case for the El Niño composite, the SST composite anomalies during La Niña are collocated with the wind anomalies (Figs. 10c,d).

**FIG. 8.** NDJ (a) El Niño and (b) La Niña composite of wind speed and direction anomalies (arrow) and sea level pressure anomalies (color). Significant composite anomalies at a 95% confidence level are marked with gray arrows for wind speed using the Student’s t test.
There is a certain degree of inverse symmetry between the El Niño and La Niña composites, discussed later. Additionally, the La Niña wind composite indicates a lower-than-normal wind anomaly along the equator near Brazil from 50° to 30°W in an ocean region that is a key region for the origin of Benguela Niños in Angola and northern Namibia.

The FMA El Niño and La Niña composites of SLP and surface wind speed and direction anomalies are presented in Fig. 11. They are very similar to NDJ, but with a stronger effect at the coast in the Benguela upwelling. The stronger northwesterly and westerly wind anomalies for El Niño are now closer to the southern African coast and occur in regions

FIG. 9. NDJ (a) El Niño and (b) La Niña composite of 200-hPa wind speed and direction anomalies (arrow) and 200-hPa geopotential anomalies.

FIG. 10. (top) FMA SST anomalies composite for (a) El Niño and (b) La Niña. (bottom) FMA surface wind speed (color) and direction (arrows) anomalies composite for (c) El Niño and (d) La Niña from 1982 to 2020.
where the pressure gradient is the tightest, explaining the SST impact at the coast in both composite and correlation maps (Figs. 4 and 10). For the La Niña composite, the SST gradient anomalies are more zonal with collocated higher easterly wind speed and cold SST anomalies visible from Brazil to southern Africa. As in NDJ for the El Niño case, a low-pressure anomaly is also present in the midlatitude anchored at the same place. The increase in wind speed off northern Namibia is also linked to higher-than-normal pressure anomalies and a shift of the pressure gradient from a southwest to a northeast direction. The association between anomalies of SLP and wind speed during La Niña and El Niño in FMA is similar to NDJ with slightly different intensity and spatial extension and consistent with the SST composite anomalies in FMA. Coastal SST changes are more significant in FMA than NDJ while large-scale SST anomalies are basinwide more significant in NDF to FMA in the subtropics; both seasons have high low-latitude anomalies of SS, SLP, and wind speed.

The surface low pressure for El Niño and high-pressure anomalies for La Niña are also present in all layers of the troposphere at 850, 700, 500 (not shown), and 200 hPa (Fig. 12). The 200-hPa anomalies are slightly less intense in FMA in the low latitude but higher in the tropics and subtropics.

4. Discussion

a. Relation between ENSO and the Benguela upwelling

Summer composite of SST anomalies for El Niño and La Niña years and correlations maps show that El Niños are associated with warming off southern Benguela and cooling of northern Benguela and vice versa for La Niñas. During ENSO, especially
in late summer. SST anomalies in the Benguela upwelling are correlated with large regions of the South Atlantic all the way to Brazil (Fig. 4). In contrast, Benguela upwelling SST anomalies are generally more correlated with regional SST in the southeast Atlantic (Fig. 3). Moreover, only during ENSO and in late summer are northern and southern Benguela significantly anti-correlated (Figs. 4, 7, and 10 and Tables 1 and 2). The ENSO correlation maps and ENSO composites (Figs. 4, 7, and 9) show a large northwest–southeast-oriented band of warm SST that encompasses the whole South Atlantic during El Niño years extending toward southern Africa’s coastline. Another feature is the warm SST anomalies in the northern Benguela and the Benguela Niños region during La Niñas in FMA. The aforementioned patterns are a consequence of changes in the atmospheric circulation over the South Atlantic. During El Niño years, there is an enhancement of the trade winds over the northern Benguela region, which favors upwelling there. On the other hand, the weakening of the upwelling favorable winds over the southern Benguela leads to the warming in this region. Those wind patterns are associated with a poleward or equatorward shift of the South Atlantic anticyclone subtropical high during La Niña and El Niño, respectively. Closer to Africa, the west and south coast of South Africa was found positively correlated to the west and south coast of South Africa (Rouault et al. 2010), and the Agulhas Bank (García-Reyes et al. 2018), south of the south coast of South Africa, is also visible in Figs. 4 and 9. The explanation is that because upwelling favorable easterly winds on the south coast do co-occur with upwelling favorable southeasterly winds on the west coast of southern Benguela as part of the same high pressure system (Rouault et al. 2010). Likewise, when a transient low pressure system, coastal lows, or cold front interrupt the upwelling by producing northwesterly winds, it will impact both regions as midlatitude low pressure systems move from west to east and coastal lows follow the coast first poleward then eastward.

b. Origin of SST changes in the South Atlantic during ENSO

Mechanisms leading to SST changes in the South Atlantic during the shift of the South Atlantic anticyclone or change in wind speed for ENSO events or opposite phase of the South Atlantic subtropical dipole are consistent with our results and discussed below. However, not many papers mention the impact of ENSO on the South Atlantic (Colberg et al. 2004; Sun et al. 2017; Rodrigues et al. 2015), and those do not mention the impact on the Benguela upwelling. Studies on the SASD have not mentioned its effect on the Benguela Current, while it was deemed the dominant mode of variability in the South Atlantic. Sun et al. (2017) have done a comprehensive study of the climatology of the South Atlantic anticyclone and its interannual variability using ERA-Interim and JRA-55 reanalysis. They found that ENSO is the main driver of the variability of the position and intensity of the South Atlantic anticyclone in austral summer, which is displaced poleward during La Niña years and equatorward during El Niño years. They have demonstrated that convective anomalies located in the tropical Pacific during ENSO events act as a remote forcing for the meridional variability of the South Atlantic anticyclone. Moreover, they have noticed a west to east displacement in the South Atlantic anticyclone related to ENSO. Our study using ERA5 SLP (Fig. S3) supports those results. Colberg et al. (2004) have shown that ENSO induces wind anomalies in the South Atlantic and modifies upper-ocean temperature by changing the net heat budget at the ocean surface, Ekman transport, and Ekman pumping leading to SST anomalies similar to the SST anomalies presented here.

c. Teleconnection between ENSO and the South Atlantic

The 200-hPa anomalies pattern in the South Hemisphere from the South Pacific Ocean to the South Atlantic Ocean shown in Figs. 9 and 12 is related to the El Niño teleconnections
and the Pacific South America (PSA) pattern, especially active during El Niño, reported by others (Mo and Paegle 2001; Puaud et al. 2017; Rodrigues et al. 2015; Dieppois et al. 2019). Moreover, El Niño creates SST anomalies in the tropics that change or increase rainfall, leading to substantial abnormal latent heat release in the troposphere. This modifies the Walker and Hadley circulation and the global midlatitude circulation. This also triggers atmospheric Kelvin waves along the equator, impacts the Madden–Julian oscillation, and triggers extratropical Rossby wave trains (An et al. 2020; Chang et al. 2020). The overall effect is at the origin of the anomalies of geopotential presented here from the surface (Figs. 8 and 10) to 200 hPa (in Figs. 9 and 12). However, there is no unified theory for the teleconnection between the Pacific and the South Atlantic during ENSO (An et al. 2020) and more work needs to be done to ascertain the dynamic of the teleconnection pattern. The impact of ENSO on the South Atlantic climate was researched by Puaud et al. (2017) while looking at the covariability of South American and the southern African inland climate in austral summer, which was found to be primarily due to the common impact of ENSO on those two regions via the Pacific South Atlantic mode (Mo and Paegle 2001). They used outgoing longwave radiation (OLR) and showed that ENSO is related to a poleward shift of the midlatitude westernlies. They found a significant positive correlation between OLR, an indication of cloud fraction and modification of the surface radiative budget, and ENSO roughly south of 30°–60°S. They found a negative correlation between 30° and 15°S in the South Atlantic that is consistent with the SST anomalies during ENSO events presented in that study. They also put forward the role of a wave train of Rossby waves in the teleconnection process. Similar mechanisms as Colberg et al. (2004) between the generation of SST anomalies in the South Atlantic and change in wind speed due to shift of the South Atlantic anticyclone for the positive and negative phase of the South Atlantic subtropical dipole were reported by Morioka et al. (2011) and Santis et al. (2020), among others, and provided crucial information on the mechanisms behind the generation and persistence of SST anomalies in the South Atlantic linked to shifting of the South Atlantic anticyclone consistent with our study. The composites of wind and SLP (Figs. 8 and 11) confirm that the local changes in the winds are associated with the impact of ENSO on the larger-scale atmospheric circulation of the South Atlantic.

d. Impact of La Niña on Benguela Niños

In northern Benguela and for La Niña years (Figs. 3b,c), there is a weakening of the upwelling-favorable winds along the coast that contributes to the warming there. In addition, the wind is lower than normal along the equator between 50° and 30°W near Brazil. This is a key region for the development of Benguela Niños through ocean wave dynamics. In NDJ and FMA in the tropical Atlantic (Figs. 10c,d), wind change occurs along the equator off Brazil, which has been associated with the formation of Benguela Niñas and Benguela Niños, respectively. Mechanisms leading to warm anomalies during Benguela Niños and their origin during those years are very well documented and will not need to be studied here (Florenchie et al. 2004; Rouault et al. 2007, 2018; Rouault 2012; Lübbecke et al. 2010; Imbol Koungue et al. 2017, 2019; Bachelery et al. 2020). The association between northern Benguela Niños and Pacific La Niñas has not been discussed in the literature and could potentially help to improve the forecast of Benguela Niño (Lübbecke et al. 2010; Rouault et al. 2018; Imbol Koungue et al. 2017, 2019). Therefore, during La Niñas, both local and remote changes in the winds over the South Atlantic corroborates the development of warm SST anomalies in the northern Benguela region. Benguela Niños would add to the SST anomalies created by the local wind anomaly. These two effects could explain the relatively higher correlation in northern Benguela than southern Benguela with ENSO.

The collocated SST and wind anomalies for El Niño and La Niña suggest a change in intensity and a shift in the South Atlantic anticyclone the low pressure system to the south with associated southeasterly, easterly, and westerly wind changes from El Niño to La Niña. It indicates that the change of SST during ENSO in the Benguela is brought about by a large and coherent and relatively homogeneous large-scale system in the South Atlantic, the Benguela upwelling being at the border of those changes.

5. Conclusions

We report here a significant but weak correlation between ENSO in austral summer and the Benguela Current upwelling sea surface temperature higher in late summer. Correlation with ENSO is positive for the southern Benguela and negative for the northern Benguela. A significant correlation exists with up to 8 months lag when the ONI ENSO index leads Benguela SST. The impact of ENSO is more substantial on the coast in late summer and is due to the effect of surface wind speed over the coastal ocean with weaker-than-normal upwelling favorable southeasterly winds during El Niño in the southern Benguela, leading to warmer-than-normal coastal SST. In contrast, during La Niñas, stronger-than-normal southeasterly winds lead to cooler-than-normal SST in southern Benguela. The ENSO effect is the opposite for northern Benguela.

The surface coastal wind change is part of an ENSO large-scale basinwide perturbation in the South Atlantic in austral summer with a stronger basinwide ENSO effect in early summer. However, non-ENSO-related SST variation in the Benguela upwelling can be as important as ENSO-related SST perturbation. Also, there is no robust relationship between the strength of ENSO and the strength of the SST perturbation, and some ENSO events do not lead to the expected changes. Changes in the Benguela are linked to changes in the intensity of the trade wind associated with the South Atlantic anticyclone. In southern Benguela, changes are also associated with variations in midlatitude low pressure systems and associated upwelling unfavorable westerly winds. La Niñas events also seem to favor the development of Benguela Niños in Angola and Namibia by decreasing wind
speed along the equator in the tropical Atlantic near Brazil, which is reported here for the first time.

ENSO has therefore an opposite effect on Northern and Southern Benguela because the South Atlantic anticyclone shifts latitudinally during ENSO. During La Niña, the South Atlantic anticyclone shift poleward, and this creates more upwelling in the southern Benguela and less in the northern Benguela. In addition, Benguela Niños tend to develop during La Niña adding to the warming in northern Benguela. During El Niño the South Atlantic anticyclone shift equatorward increasing upwelling in the northern Benguela and decreasing upwelling in the southern Benguela.

This study shows the potential for SST seasonal predictability in late austral summer in the Benguela Current upwelling system due to the existing lead-lag correlation of ENSO in relation to the Benguela SST. The impact of El Niño–Southern Oscillation on the southern African climate is well documented and provides skill in the seasonal forecast of rainfall. Former work on limitations and success of rainfall forecast or dispersion of the information offers a fast learning curve and many ideas to kick start operational SST forecasting in the region. As SST and upwelling strength are intimately related to the health of the marine ecosystem and fisheries, forecasting SST should be part of the sustainable management of the marine ecosystem in the Benguela upwelling.

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Data availability statement. All data used in this study are publicly available and can be downloaded freely. The NOAA Optimally Interpolated V2 SST is available at https://psl.noaa.gov/. The monthly ERA5 data are available at https://cds.climate.copernicus.eu.

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