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Ocean and Wave Climate Variability in West Africa, and Implications for Alongshore Sediment Transport on the Senegal-Mauritania Coast

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ABSTRACT

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The east Atlantic wave climate in the region of West Africa is dominated by north-northwesterly high energy swell. Wave conditions are variably modified inshore, but a strong obliquity in wave approach remains, leading to a predominance of north-south sediment transport. Implications for coastal sediment movement in the event of deviations or progressive shifts in offshore wave climate are important in driving change in patterns of erosion and deposition. Here, ERA5 wave data covering the last 6 decades (1940-2023) is analysed at annual and seasonal scales to understand the variability in wave climate over time and to explore the association with key climate drivers such as ENSO, NAO, and AMO. The winter season is considered in more detail to investigate extreme wave parameters. Results show that wave height (>2.5m), period (14s) and were more frequent in the 1950s and over the 2000-2018 period, with extreme wave height (3.92m) being associated with a direction of 335.60°. Wave direction increased by 4.08° between 1940 and 2023, which influences sediment transport direction patterns along the coast. NAO has a greater influence on winter swell wave height and direction than ENSO, which only moderately affects the local wave climate.

ADDITIONAL INDEX WORDS: *Ocean-wave variability, North Atlantic, ERA5, winter swell, sediment transport.*

INTRODUCTION

Ocean and wave climate play a pivotal role in shoreline and coastal dynamics, and can be particularly sensitive to climate change. Ocean climate drivers like El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Atlantic Multidecadal Oscillation (AMO) that capture climate fluctuations and anomalies in the Pacific and North Atlantic, have been shown to exert some control on shoreline position and sediment supply in estuarine and deltaic systems worldwide (Storlazzi and Griggs, 2000; Dada et al., 2016; Ghanavati et al., 2023). Recent research outlined some influences of ENSO on shoreline position variability and sediment supply in estuarine and deltaic systems all over the world (Almar et al., 2023), while the NAO influence on coasts appears to decrease on latitudinally (Hilton et al., 2020). In this context, the coast of the wave-dominated Senegal estuary coast that straddles Senegal and Mauritania is characterised by a southward-migrating sand spit. This study explores the variability in east Atlantic Ocean wave climate over the period 1940 to 2023 and investigates the role of ocean drivers such as ENSO, NAO, and AMO in driving change in wave processes along the Mauritania-Senegal coast.

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METHODS

Hourly ERA5 wave data spanning the years 1940-2023, derived in the ECMWF reanalysis, was sourced from the Copernicus Climate Data Store to explore long-term variability in wave climate along the Senegal estuary based on a single data point offshore from the Senegal estuary (Figure 1). Wave climate was analysed to capture statistical summaries of annual and seasonal wave parameters (wave height, time period, and direction); extreme values were also identified. The ocean drivers ENSO, NAO, and AMO were represented by their respective indices (sourced from: National Oceanic and Atmospheric Administration [ENSO] and National Center for Atmospheric Research [NAO]).

To ensure comparability between wave data and ocean indices (which varied in record interval from hourly (waves) to bimonthly (ENSO)) when performing correlation tests, data (years mentioned above) were reduced to Winter (December-March) and Summer (June-September) means to capture seasonal variability over years. Winter is the most relevant season in the year for swell and ocean climate analysis when considering ANACIM (2018, 2021, 2023) annual alerts about winter swell heights and the greater potential fluxes that can be mobilised by larger winter waves. Analyses were conducted in a Python environment using numerical computing libraries (xarray, netcdf4, numpy, pandas, scipy, matplotlib) to manage arrays (ERA5 netCDF files), data preprocessing, cleaning, exploration, statistical analysis and visualisation.

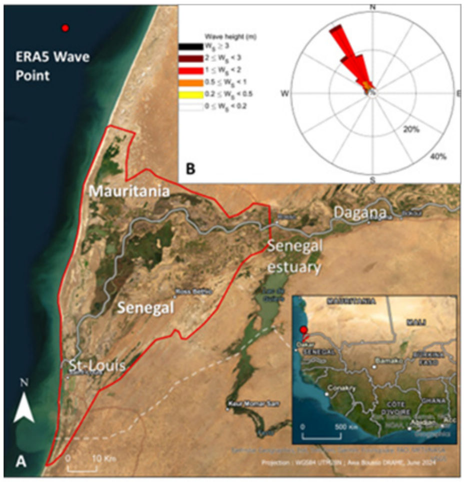

Figure 1. (A) The Mauritania-Senegal coastline bordering the east Atlantic Ocean: (B) Wave rose summary of the 1940-2023 wave climate offshore from the Senegal estuary.

RESULTS

1940-2023 Wave Climate Variability

Hourly wave height averaged 1.32m over the 1940-2023 period, with a standard deviation of 0.38m (Figure 2); 86% of wave heights were in the 0.75-1.75m range. The average hourly wave period is 7.56s, with a standard deviation of 1.78s. Monthly average wave period varies between 6 and 10 seconds. Wave direction is dominated by northwesterlies (Figure 2C); the direction range 315°-345° represents 58.5% of wave occurrence The top 10 extreme wave heights (Table 1) are not evenly distributed through time. None are prior to the 1960s, but since then, high waves have occurred once or twice each decade, with several years between occurrences except for 1983/1985 and 1996/1997, when successive large waves occurred within a couple of years. Recently, extreme wave periods are concentrated during 2000-2018 with peaks of 17.22s (07/01/2014 18:00) and 16.80s (18/11/2018 21:00). The top 10 wave periods are not explicitly coincident with high waves. Extreme heights and periods only occur within days of each other in December 1997 (5 days) and November 2018 (1 day). Four of the largest wave periods occurred in the 2010s, whilst the earliest date in the list is January 1959. Most extreme waves occurred in winter, with February being the most common month for large wave heights and January/February for the period.

Ocean Climate Variability

ENSO is a climate phenomenon inducing changes in sea surface temperatures in the tropical Pacific Ocean, and includes the El Niño and La Niña events. During El Niño events, weaker easterly winds lead to warmer surface waters in the east Pacific; during La Niña, stronger easterly winds push warmer water to the west Pacific, and upwelling brings cooler water to the east Pacific coast (Tsonis et al., 2003). Its influence has been understood in terms of sea level anomalies, droughts, floods, and hurricanes, particularly affecting the east Pacific region (Patricola et al., 2020; (Lin et al., 2020). Over the 1979-2023 period, the winter and summer ENSO index (Figures 3A, B) show a similar pattern through time, characterised by alternating phases of positive and negative values. Positive ENSO index (El Niño) was most prominent in 1982-1983, 1997-1998, and 2015-2016. Negative phases (La Niña) are most prominent in winter 2011 (-1.75) and 1999 (-1.24) and summer 2010 (-2.36) and 2022 (-1.92).

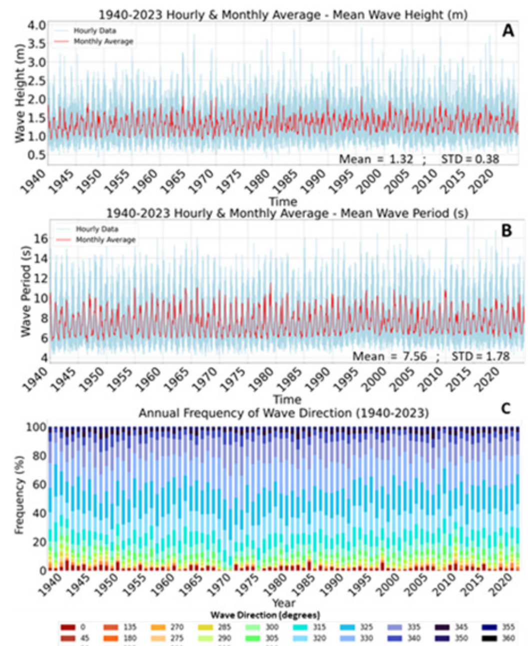

Figure 2. Hourly and monthly mean wave height (A) and period (B), and annual wave direction frequency

Table 1. *Extreme wave height (Hs) and period (Tp) over 1940-2023.*

Date & Time	Hs (m)	Wave Dir (°)	Date & Time	Tp (s)	Wave Dir (°)
10/01/1996 09:00	3.92	324.06	2014-01-07 18:00	17.21	325.66
26/12/1983 09:00	3.87	322.56	2018-11-18 21:00	16.80	323.55
22/02/1966 05:00	3.73	327.45	1997-12-15 15:00	16.45	313.97
19/11/2018 08:00	3.70	322.48	2003-03-11 13:00	16.44	327.09
09/02/2010 11:00	3.67	314.50	1966-01-13 16:00	16.07	314.53
20/12/1997 05:00	3.63	325.23	1985-02-07 19:00	16.05	320.01
11/02/1979 07:00	3.60	316.80	1959-01-05 04:00	16.01	308.13
14/04/2003 21:00	3.35	329.82	1987-02-27 19:00	15.99	312.68
08/02/1985 09:00	3.34	320.21	2010-02-15 17:00	15.98	303.39
26/03/1969 07:00	3.34	321.48	2017-04-03 22:00	15.87	313.32

NAO is an important climatic parameter influencing atmospheric circulation, sea surface temperatures, precipitation and temperature patterns in the North Atlantic (Figures 3C and D). The index captures the atmospheric pressure gradient between the Azores subtropical anticyclone (high pressure) and subpolar Iceland depression (low-pressure system) (Hurrell & Deser, 2010). A positive winter NAO index (observed in the 1920s, 1990s and 2010s) is associated with milder, wet and windy conditions in northern Europe and the opposite in southern Europe (Figure 3C); enhanced positive summer indices occur in 1920s, 1940s, 1950s and 1960s. Negative NAO reflects strong westerlies in West Africa (weak westerly winds in northern Europe) with a greater variability noted during winter (STD = 1.05, max = -3.15 in 2010), confirming the occurrence of anomalies during this season. Simultaneously, negative summer NAO reveals minimums of -3.40 in 2023, -2.55 in 1922, -2.375 in 1976, and -1.875 in 1877 and a lower variability (STD = 0.92) than in winter.

The Atlantic Multidecadal Oscillation (AMO) is calculated from observed sea surface temperature anomalies in the North Atlantic (Alexander et al., 2014). The alternation of winter and summer AMO phases (Figure 3 E and F) show a common pattern and variability with respective standard deviation of 0.14 and 0.17. Positive AMO periods are characterized by warmer conditions in the North Atlantic, cooler in West Africa particularly important over 1920-1970, with winter extremes of 0.29 in 1955, 0.26 in 1962, 0.25 in 2008 and 0.23 in 1956, whereas 0.53 in summer 1937, 0.41 in summer 2010, 0.37 in summer 1952 and 0.36 in summer 1955. Negative periods correspond to cooler-than-average temperatures, identified in both winter and summer phases around 1963-1998, respectively, of -0.36 in winter 1972 and -0.41 in summer 1974. These results indicate a rise in sea surface temperatures during the winter season and extremes observed in the years mentioned above, while little cooling anomalies occur during summer.

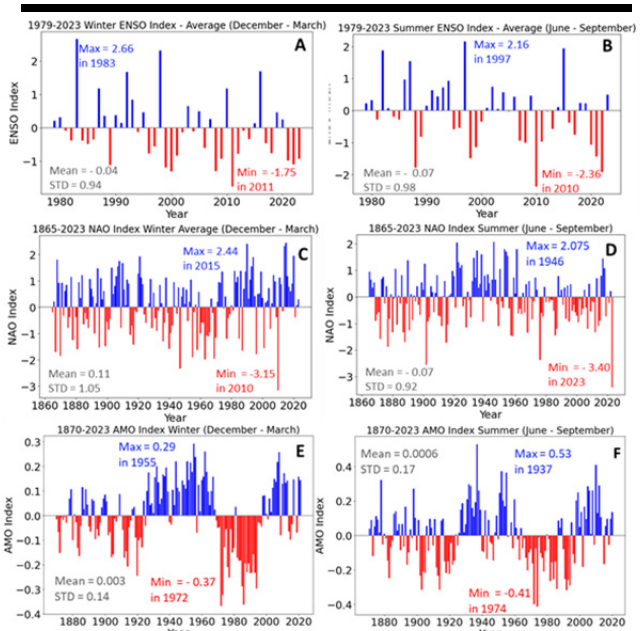

Figure 3. Ocean variability: (A)Winter ENSO (B), Winter NAO, (C) Winter AMO, (D) Summer ENSO, (E) Summer NAO, (F) Summer AMO Note different axis scales throughout.

Winter Ocean Indices and Anomalies in the Local Wave Climate

Seasonal ocean drivers' variability can induce non-negligible implications for the local wave climate, for instance with the Senegal National Weather Agency annual alerts about winter swell episodes (>= 3m)(ANACIM 2018, 2021, 2023). Swells are long-wavelength winds travelling vast distances with little energy loss transferred to the seabed, influencing coastal sediment transport.

Correlation tests between winter swell and ocean drivers have been conducted. The specific correlation between ocean index and swell direction has been assessed focusing on northwesterly (> 315°) and westerly (245-314°) swells, detected from 1979, and respectively representing 83.01% and 11.99% of the winter swell over 1980-2023. There is a moderate negative correlation between ENSO and northwesterly (> 315°; R = - 0.29; p= 0.05) and westerly swells (245-315°; R = - 0.22; p > 0.1). No correlation was detected between winter ENSO and swell height (R=0.06, p=0.96). Positive winter ENSO (El Niño events occurring during winter, weaker trade winds, low wave energy) is then associated with a more pronounced swell direction decrease (westerlies) than swell period along Senegal-Mauritania.

NAO is well-known for influencing West Africa's hydro-climatic variability (Nouaceur & Murarescu, 2020), even if its potential impact on ocean and wave climate is poorly known. Unsurprisingly, northwesterly swell illustrates the strongest positive correlation with NAO (R=0.61, p-value<0.01) compared to a moderate relation with westerly swell (R = 0.33 and p < 0.05). It is followed by swell height presenting a strong negative correlation (R=-0.52, p-value<0.05), and a moderate negative relation with wave period (R=- 0.35, p-value<0.01). In other words, winter NAO positive phases (westerly winds and stormy conditions in northern Europe, calmer westerlies conditions along Senegal) are linked with a more northwesterly swell direction and a moderate decrease of swell heights and period. On the contrary, over winter, NAO negative events (westerly winds dominance in West Africa) induce a significant decrease in swell direction (more westerly swells), increase in swell height and a moderate increase in swell period.

Unexpectedly, AMO has no correlation with swell height (R = - 0.09, p> p>0.1) and period (R = - 0.01, p>0.1) with R values near 0, for both northwestward and westward swells (respectively R = - 0.034 ; p>0.1and R = - 0.13 and p>0.1).

DISCUSSION

Results highlighted variability in wave climate throughout 1940-2023, with successive high wave occurring in 1983/1985 and 1996/1997, and extreme periods concentrated in 2000-2018. Extreme waves are only found between November and January. Similarly, ENSO and NAO analysis demonstrated greater swell influence during winter. It was found a reinforcement of winter northwesterly swells, under the main influence of NAO positive phases (weak westerlies) and a low to moderate El Niño drive, also present in wave period increase. Greater winter swell period and height negatively correlate with winter NAO negative periods, while AMO does not influence the winter swell conditions along the Senegal estuary. Such wave climate patterns and ocean drivers anomalies may reflect the impact of global warming with more pronounced seasonal anomalies.

Similarly, Lozano et al. (2004) demonstrated that coastal storminess strongly correlates positively with NAO winter phases on the Romanian Black Sea Coast and suggested similar influences on other coasts, potentially affected by their local climatic variability. Only a few recent studies have assessed potential correlations between ocean and wave climate variability in Senegal and West Africa. Our findings are in accordance with Sadio et al. (2017), who found that dominant swells are WNW-N oriented for an average mean of 325°, seasonal swell and winter activity during winter in the northern hemisphere. They also attributed wind waves to passages of the ITZC over Senegal (Intertropical Convergence Zone) during autumn and spring. Although Samou et al. (2023) work focused on general wave climate and not swell, they found wave height and mean wave period have a negative correlation with NAO, while wave direction shows a strong positive correlation with NAO on the Grande Côte (Dakar-Saint-Louis).

Recent investigations underscore climate change as a key factor driving wave climate variability and energy shifts in the tropical Atlantic, affecting shoreline dynamics. Chowdhury et al. (2020) research on future wave climate along the Indian coast predicts future higher wave heights and longer wave periods (at least 20%), indicating a greater swell occurrence. They also expect shifts in wave direction with more southerly waves. In West Africa, wave climate studies are understudied, but among emerging studies, Agbetossou et al. (2023) discovered wave height was the main driver in sediment transport along Denu beach in the Volta region (Ghana). They explained more significant wave heights induced greater sediment transport due to wave-breaking. Dada et al. (2016) illustrated how augmentation of wave energy and shifts in wave direction in the Gulf of Guinea increased the alongshore sediment transport along the Niger Delta shoreline. More specifically, Almar et al. (2015) analysis detected swell-generated longshore sediment transport had a greater magnitude than wind waves, confirming observations made in southeast Asia also occur in the Gulf of Guinea. McCloskey et al. (2013) found that positive NAO events induced more tropical cyclones along the US eastern coast, generating more north-westerly swell waves reaching Senegal shores, including the Senegal estuary.

Implications for Coastal Sediment Transport along the Senegal Estuary Coast

Winter seasonal anomalies (El Niño, NAO) might be characterised by longer swell periods leading to more wave refraction, inducing a more significant cross-shore component in wave energy flux, as Adams et al. (2011) suggested. Greater swell heights observed during winter could also favour offshore sediment transport and temporary storage/accumulation in offshore bars along the Senegal estuary. There may be an increase in winter swell heights in the near future and more northerly directions along the Senegal estuary. These direction might influence flux direction alongshore and reinforce the predominant southern longshore drift. Analysing localised points along the coast, Sadio et al. (2017) confirmed this hypothesis, showing the open coast shoreline fronting the Senegal estuary is mainly under the influence of the southwards swell-generated longshore drift, bringing 611×10^3 m^3/year in comparison with 59×10^3 m^3/year from wind-wave transport without specifying intra-annual/seasonal variabilities. Our study suggests that swell-driven longshore sediment transport primarily occurs and increases during winter, driven by NAO-negative phases (strong westerlies) increasing swell height and reinforcing the north-south longshore drift direction. Weakened north-south coastal drift could result from more westerly swells (direction decrease) occurring during ENSO positive events (El Niño). These observations could affect deposition patterns along the Senegal estuary and impact slope and beach stability, particularly under stormy conditions. Nevertheless, other parameters such as river flow, tides, coastal engineering (Nouakchott and Ndiago ports, Saint-Louis seawall), and local sea level rise may also play a role in the coast's future evolution.

CONCLUSIONS

Ocean and wave climate conditions presented variability along the Senegal estuary. While wave height, period, and direction peaks tend to occur during winter, suggesting swell presence, NAO-positive phases (weak westerlies) moderately drive winter northwesterly swell coinciding with El Niño (ENSO positive events). NAO negative episodes (strong westerlies) occurring during winter can significantly increase swell height, resulting in an increase of sediment transport along the Senegal-Mauritania coast. ENSO has a limited influence on the swell climate, with a moderate negative association with swell direction and a low positive correlation with swell period. AMO has no direct impact on local wave climate conditions. More northwesterly swell conditions could increase the north-south longshore drift direction during winter. This paper's outcomes also suggest greater swell height and periods might amplify coastal sediment transport volume during winter (particularly winter NAO negative phases). This supply may result in accumulation along the estuary and potentially some cross-shore processes generating offshore bars and sediment accumulation near the Langue de Barbarie.

Further investigations could monitor winter swell conditions (height, period, direction) and their influence on deposition erosion/accretion patterns and seasonal shoreline change. To develop a full picture, bathymetric analysis alongshore and in the mouth of the Senegal estuary could also be conducted to capture landforms responses to winter swell. This study has a number of important implications for coastal management and decision-making. Connecting winter swells and bathymetric monitoring could provide more precise warning systems for fishers' navigation in the nearshore zone. Beyond disseminating swell alerts, implementing local buoys to enhance the existing wave measurements (velocity, direction, height) will allow developing more accurate numerical models, including infrastructures' role in the complex coastal hydrodynamics of the Senegal estuary.

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