

**OCEAN-ATMOSPHERE INTERACTIONS IN NORTHWEST AFRICAN AND
GULF OF GUINEA COASTAL UPWELLING SYSTEMS**

BY

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A thesis of the Doctoral Research Programme in West African Climate Systems (DRP-WACS) under the West African Science Service Centre of Climate Change and Adapted Land Use (WASCAL), in the Department of Meteorology and Climate Science submitted to the School of Postgraduate Studies in partial fulfilment of the requirements for award of the degree of Doctor of Philosophy in Meteorology and Climate Science of the Federal University of Technology, Akure, Nigeria.

June, 2025

DECLARATION

I thereby declare that I wrote this Thesis and is a correct record of my own research work. It has not been presented in any previous application for any degree of this or any other University. All citations and sources of information are clearly acknowledged by means references

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CERTIFICATION

We certify that this Thesis entitled “Ocean-Atmosphere Interactions in Northwest African and Gulf of Guinea Coastal Upwelling Systems” is outcome of the research carried by DAMETOTI YAMOULA under the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) Doctorate Research Programme in West African Climate Systems (DRP-WACS) in the Department of Meteorology and Climate Science, The Federal University of Technology, Akure.

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ABSTRACT

The Ocean and Atmosphere interaction is a complex system that requires particular attention in coastal upwelling systems due to their nutrient supply, biological productivity, influence on local weather patterns and regional climate variability, and socio-economic importance. The present study investigates the behaviour of ocean, atmosphere, and their interactions in the coastal upwelling systems of Northwest Africa and Gulf of Guinea during ocean cooling and warming episodes, with a focus on the dynamical and interannual variability of Senegal-Mauritania and Gulf of Guinea upwelling regions. Multiple datasets including different physical and biogeochemical variables, several upwelling indices and statistical tools were used. Results highlighted the seasonal dynamic and interannual variability of two upwelling systems modulated by both local and remote forcings such as wind stress-driven Ekman dynamics, mesoscale and cyclonic eddies, regional ocean currents, Equatorial dynamics including Kelvin and Rossby waves and coastal trapped waves, and large-scale climate drivers. The results also underlined the influence of other geographical and environmental factors such as coastal shape and orientation, the geographical position of upwelling system, the motion of Intertropical convergence zone, and Azores and Saint Helena high pressure systems that modulated pressure and temperature gradients. The study identified marine heat waves, which are characterized by weakened Ekman transport and suppressed vertical mixing, as emerging stressors of coastal upwelling dynamics. These events significantly impact coastal marine ecosystem productivity, surface air temperature, and precipitation, underscoring the importance of addressing them in local weather predictions. The findings also demonstrate the ongoing limitations of the latest generations of the Coupled Model Intercomparison Project Phases 5 and 6 (CMIP5 and CMIP6) in capturing coastal processes and upwelling features, and call for the use of more powerful artificial intelligence predictive models, such as long short-term memory and convolutional

neural networks (LSTM-CNN), to improve weather predictions and reduce uncertainties in climate model simulations in coastal upwelling regions.

DEDICATION

To you, my family, who have supported me physically and morally from near and far in this noble task and trial of my life, to whom I dedicate this work.

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ACRONYMS

Acronym	Meaning
AC	Azores Current
ACT	Atlantic Cold Tongue
AI	Artificial Intelligence
AMM	Atlantic Meridional Mode
ANNs	Artificial Neural Networks
AMO	Atlantic Multi-decadal Oscillation
ATL3	Atlantic Niño
CC	Canary Current
CMIP	Climate Model Intercomparison Project
COBE	Centennial in situ Observation-Based Estimates
CNNs	Convolutional Neural Networks
CTW	Coastal Trapped Waves
CUC	Canary Upwelling Current
CUI	Cumulative Upwelling Index
DJF	December-January-February
DL	Deep Learning
DKRZ	Deutsche Klima Research Zentrum
EBUSs	Eastern Boundary Upwelling Systems
ECMWF	European Centre Medium-Range Weather Forecasts
EEA	Eastern Equatorial Atlantic
EEZ	Exclusive Economic Zone
ENSO	El Nino Southern Oscillation
EOF	Empirical Orthogonal Function

GBR	Gradient Boosting Regression model
GC	Guinea Current
GCMs	Global Climate Models
GEBECO	General Bathymetry Chart of the Ocean
GGUS	Gulf of Guinea coastal Upwelling System
GLORYS	Global Ocean Ranalysis
IOD	Indian Ocean Decade
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence zone
JJA	June-July-August
LMEs	Large Marine Ecosystems
LSTM	Long Short-Term Memory
MAE	Mean Absolute Error
MAM	March-April-May
MHWs	Marine Heatwaves
ML	Machine Learning
MLD	Mixed Layer Depth
MMM	Multi-Model Mean
MODIS	Moderate Resolution Imaging Spectroradiometer
NOAA	National Oceanography and Atmospheric Administration
NOAA20CR	NOAA-CERES 20 th Century Reanalysis
NACW	Northern Atlantic Central Waters
NAO	North Atlantic Oscillation
NASG	North Atlantic Subtropical Gyres
NATG	North Atlantic Tropical Gyres

NCEP	National Centre OF Environmental Prediction
NECC	North Equatorial Counter Current
NOI	North Ocean Index
NPP	Net Primary Productivity
ONI	Ocean Niño Index
ORAS5	Ocean Renalysis System version five
PC	Poleward Current
PCAs	Principal Component Analyses
PDO	Pacific Decadal Oscillation
PUC	Poleward Upwelling Current
RFR	Random Forest Regression model
RMSE	Root Mean Square Error
RNNs	Recurrent Neural Networks
SACW	Southern Atlantic Central Water
SLA	Sea Level Anomaly
SMUS	Senegal-Mauritania coastal Upwelling System
SOI	Southern Oscillation Index
SHAP	SHApIey exPlanations
SSH	Sea Surface Height
SSP	Share Socio-economic Pathway
SST	Sea Surface Temperature
SSS	Sea Surface Salinity
STI	Start Transition Index
ROMS	Regional Ocean Model System
UI	Upwelling Index

WAM	West African Monsoon
WSCD	Wind Stress Curl Driven

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Coastal upwelling is an ocean, atmosphere and land interaction process driven by several physical mechanisms. Coastal upwelling process was traditionally related to the combined effects of wind stress forcing and Earth's rotation (Ekman, 1905). Studies in the eastern Atlantic boundary systems (Djakouré *et al.*, 2014; Brandt *et al.*, 2023) have demonstrated that coastal upwelling can be modulated by multiple local and remote forcings, including Ekman transport, wind stress curl, Kelvin and Rossby waves, coastal trapped waves, interactions between ocean currents and the coastline, mesoscale eddies, and regional and large-scale climate modes (e.g., ENSO, NAO, Atlantic Niño, and AMO), global warming, and climate change (Bograd *et al.*, 2023), as well as other geographical and environmental factors (Bakun, 1975). Four major eastern boundary upwelling systems (EBUSs), including Benguela, California, Canary and Humboldt upwelling systems, are well documented because of their nutrient supply, biological productivity, influence on the local weather and regional climate systems, and socio-economic importance (Bakun *et al.*, 1973; 1975; 1978). They contribute about 8% of the global marine primary production and more than 20% of the global fish catches, while covering only 2% of the global ocean surface (Pauly and Christensen, 1995).

Coastal upwelling plays a crucial role in regulating the ocean-atmosphere system by bringing deep, cold, and nutrient-rich waters to the surface, enhancing biological productivity. They also influence local weather patterns and regional climate variability. In the Northwest African coastal upwelling system, one of the eastern boundary Atlantic upwelling systems, several physical mechanisms have been proposed to understand upwelling process. This

upwelling region which is the domain of this study, includes Senegal-Mauritania and Gulf of Guinea upwelling systems.

The Senegal-Mauritania upwelling system (SMUS) is primarily associated to the equatorward trade winds driven offshore Ekman transport modulated by Azores high pressure system and the position of the Intertropical convergence zone (ITCZ). This upwelling system is also found to be modulated by other local mesoscale and remote forcings such as wind stress curl driven coastal divergence, the regional ocean currents such as Poleward current and North Equatorial counter-current, (NECC) (Benazouzz *et al.*, 2014; Klenz *et al.*, 2018; Kounta *et al.*, 2018), the eastward propagation of Kelvin waves (Polo *et al.*, 2008), regional and large-scales climate drivers such as Atlantic Meridional Mode (AMM), Dakar Niño/ Niña, El Niño Southern Oscillation (ENSO) (Oettli *et al.*, 2016, Wade *et al.*, 2023), bathymetry, coastal shape and other hydrometeorological factors that influence thermocline depth and stratification (Ndoye *et al.*, 2014).

The Gulf of Guinea is modulated by complex air-sea interactions. Coastal upwelling in this region is linked to the strengthening of Ekman suction, effect of eastward propagation of Kelvin waves and poleward propagating of coastal trapped waves (Moore *et al.*, 1978; Clarke 1979; 1983; Servain *et al.*, 1982, Picaut, 1983; Philander, 1990; Polo *et al.*, 2008; Illig *et al.*, 2024), interactions between regional ocean currents and coastline such as the Guinea current and NECC (Ingham, 1970, Colin, 1988; 1991; 1993; Djakouré *et al.*, 2014; 2017), cape effects and cyclonic eddies (Marchal and Picaut, 1977; Binet, 1997), turbulent mixing (Brandt *et al.*, 2023) and large-scale climate drivers (e.g., ENSO, Atlantic Niño/Niña) that influence thermocline depth, stratification and upwelling variability (Lübbecke *et al.*, 2018, Richter and Tokinaga, 2020).

In Addition, the ongoing global warming and climate change explain the recent upwelling variability (Bograd *et al.*, 2023). Bakun (1990) predicted intense upwelling due to the strengthening of upwelling-favourable winds in the Eastern boundary upwelling systems (EBUSs) under climate change. However, this hypothesis supported by Sydeman *et al.* (2014) has been challenged in recent studies (e.g., Chang *et al.*, 2023). In the SMUS as other EBUSs, climate models are predicting the northward shift of upwelling signal.

Understanding all these complex interplays between atmospheric and oceanographic, local and remote forcing mechanisms, is essential for predicting upwelling variability and its implications for marine ecosystems and regional climate trends.

1.2 Problem Statement

Coastal upwelling in the eastern Atlantic, including the Northwest African and Gulf of Guinea systems, is influenced by a combination of local and remote forcing mechanisms. These mechanisms include wind-driven Ekman dynamics (Ekman, 1905); mesoscale and cyclonic eddies (Marchal and Picaut, 1977; Binet, 1997); regional ocean currents (Djakouré *et al.*, 2017; Klenz *et al.*, 2018; Kounta *et al.*, 2018); equatorial wave dynamics, such as Kelvin and Rossby waves (Polo *et al.*, 2008); and geographical and environmental factors (Bakun *et al.*, 1978). Other key drivers include the latitudinal position of the Intertropical Convergence Zone (ITCZ), the Azores and Saint Helena high-pressure systems, and large-scale climate modes, such as the El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Meridional Mode (AMM) (Oettli *et al.*, 2016; Wade *et al.*, 2023), as well as the impact of anthropogenic climate change (Bograd *et al.*, 2023).

Despite extensive research into the mechanisms governing coastal upwelling, the predictability of these systems, particularly their dynamical and interannual variability,

remains limited. This is largely due to gaps in our understanding of the primary drivers of coastal upwelling in the tropical Atlantic.

Previous generations of global climate models, including CMIP5, have demonstrated significant biases in upwelling regions (Sylla *et al.*, 2019; Varela *et al.*, 2021; Ideki and Lupo, 2024), underlining the need to evaluate improvements in the latest model outputs (e.g., CMIP6). Although regional modeling in the Northwest African (Ndoye *et al.*, 2014; 2017; Vázquez *et al.*, 2022; 2024) and Gulf of Guinea (Djakouré *et al.*, 2014; 2017; Illig *et al.*, 2024) coastal upwelling regions has reduced these biases and improved the representation of coastal processes, uncertainties persist, particularly concerning the mechanisms that constrain the predictability of weather and upwelling in the tropical Atlantic.

These uncertainties highlight the potential role of artificial intelligence and technology in advancing our understanding and forecasting capabilities for coastal upwelling systems and associated weather patterns along the Northwest African and Gulf of Guinea coasts.

While numerous studies have examined the physical mechanisms, drivers, and ecological impacts of upwelling on fisheries (Koné *et al.*, 2017; Amemou *et al.*, 2020), local weather, and regional climate systems (Brandt *et al.*, 2011; Caniaux *et al.*, 2011; Rodríguez-Fonseca *et al.*, 2015; Coëtlogon *et al.*, 2011), relatively little is known about how MHWs influence the dynamics and productivity of coastal upwelling in these regions.

Thus, the intensity, frequency, and predictability of coastal upwelling events under the influence of ongoing climate change, including extreme events such as marine heatwaves, remain major scientific challenges.

The present study addresses this gap by investigating ocean-atmosphere interactions in the Northwest African coastal upwelling system, specifically in the Senegal-Mauritania (10°–25°N) and in the Gulf of Guinea (4°–7°N) coastal upwelling region, under the influence of

MHW episodes. Using a combination of in situ observations, satellite data, ocean and atmosphere reanalysis products, and climate model outputs, the study highlights the new stressors affecting air-sea interactions and upwelling dynamics during boreal winter-spring and summer seasons.

Scientific Research Questions

The fundamental question of this study is how does the air-sea interactions drive changes in upwelling? To answer this central question, the following interrogations are addressed:

- (i) Many studies have shown that coastal upwelling in the Northwest African and Gulf of Guinea regions cannot be explained by wind forcing alone. As a result, several additional factors have been considered as upwelling drivers to better understand the dynamical and interannual variability of these systems. However, what are the current characteristics of the Northwest African and Gulf of Guinea coastal upwelling systems?
- (ii) Although the drivers and impacts of upwelling are well documented along the Northwest African and Gulf of Guinea coasts, the factors influencing changes in its intensity and frequency are not well understood. The key question is how extreme temperature events, known as MHWs, influence upwelling dynamics and productivity.
- (iii) A continuous biases were observed through CMIP generations of models in the global ocean. Thereby, what are the uncertainties of the CMIP5 and CMIP6 climate models in simulating upwelling features in the Northwest African coastal upwelling systems?
- (iv) Physical and dynamical climate models are used as numerical tools to simulate upwelling features. Recently, artificial intelligence tools have been used as powerful instruments for predicting oceanic, atmospheric or meteorological and climatic events. In this study, we also evaluate how traditional machine learning models, including Random

Forest and Gradient Boosting, and advance Deep Learning architectures such as Long-Short Term Memory (LSTM) and Convolutional Neural Network (CNN) can predict the variability of Northwest African coastal upwelling at the interannual scale.

1.3 Aim and Objectives

The aim of this study is to investigate air-sea interactions in the Northwest African and Gulf of Guinea coastal upwelling systems during ocean cooling and warming episodes.

The specific objectives are to:

- (i) characterize the dynamics and interannual variability of Northwest African and Gulf of Guinea coastal upwelling systems;
- (ii) evaluate the impacts of marine heatwaves (MHWs) on coastal upwelling dynamics and ecosystem productivity;
- (iii) assess the capacity of climate model Inter-comparison Phases 5 and 6 outputs in to capture upwelling features in both Senegal-Mauritania and Gulf of Guinea coastal upwelling regions;
- (iv) predict the variability of coastal upwelling on interannual time-scale with Machine Learning and Deep Learning statistical models.

1.4 Motivation and justification of the study

The Northwest African and Gulf of Guinea coastal upwelling systems are critical components of the regional climate and oceanographic dynamics. These systems play a central role in regulating local weather, regional climate patterns, marine productivity, and ocean-atmosphere interactions. Their high biological productivity supports important fisheries that contribute significantly to food security and socioeconomic stability across West African coastal countries.

The functioning and variability of these upwelling systems are closely linked to both atmospheric and oceanic conditions. Consequently, changes in climate, whether driven by natural variability or anthropogenic forcing, can alter the upwelling regimes, affect marine productivity, and disrupt the timing and sustainability of fisheries and related coastal economic activities.

Although the fundamental mechanisms of upwelling in regions such as the Senegal-Mauritania zone (Ndoye *et al.* 2014, 2017, Vázquez *et al.* 2022, 2024) and Gulf of Guinea (Djakouré *et al.* 2014, 2017, Brandt *et al.* 2023) have been documented, a deeper understanding of the complex air-sea interactions and their drivers is still necessary. This is especially important in the context of global warming and ongoing anthropogenic climate change.

CHAPTER TWO

LITERATURE REVIEW

2.1 Coastal Upwelling Mechanisms and Processes

Coastal upwelling is an ocean-atmosphere and coastal-land interaction process that drives the rise of nutrient-rich cold waters onto the continental shelf under the combined influence of intense upwelling-favourable wind stress and Earth's rotation (Ekman, 1905).

Vagn Walfrid Ekman's (1905) theory describes how wind stress drives ocean surface dynamics, creating a spiraling motion in the water column known as the Ekman Spiral. According to this theory of wind-induced ocean circulation, when ocean surface waters with a homogeneous density structure are subjected to persistent surface winds, their motion is governed by the equilibrium between the Coriolis force and wind-induced frictional force (Fig. 2.1). This mechanism leads to net water transport (Ekman transport), which plays a crucial role in coastal upwelling and downwelling processes. Strong winds blowing parallel to the coast create a divergence of surface waters, leading to alongshore transport (Ekman transport) within the Ekman layer. This process results in the upwelling of cold, nutrient-rich waters from deeper layers to replace the displaced surface waters. This Ekman theory has been instrumental in explaining the phenomena of upwelling-downwelling and their impact on nutrient supply, primary productivity, and marine ecosystems, through the following equation:

$$\vec{M}_E = \frac{\vec{\tau}}{\rho \cdot f} \quad (2.1)$$

Where $\vec{M}_E$ is Ekman transport vector; $\vec{\tau}$ is wind stress (N/m^2), ρ is the constant seawater density ($\sim 1025 \text{ kg/m}^3$), and f is the Coriolis parameter (s^{-1}). $f = 2\Omega \cdot \sin\phi$ where $\Omega = 7.2921 \times 10^{-5} \text{ rad/s}$ is the Earth's angular velocity; ϕ is the latitude.

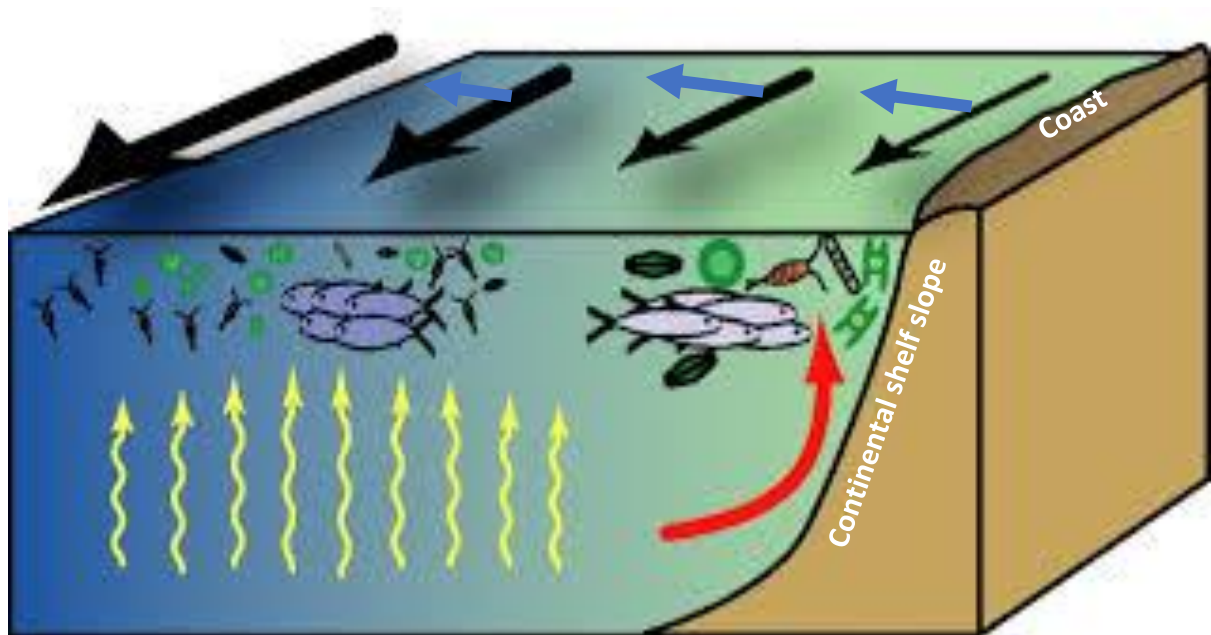


Figure 2.1: Schematic of the wind-driven coastal upwelling process (online source).

Another important theory on large-scale ocean circulation and vertical water movements was developed by Harald Sverdrup (1947). Sverdrup's theory explains the relationship between wind stress and large-scale ocean circulation, focusing on the vertical water motion driven by the wind stress curl. It describes the balance between wind-driven forcing and the Coriolis effect, which governs wind-driven ocean circulation.

In regions where wind stress varies spatially, the resulting changes in surface pressure gradients cause vertical water movements, leading to upwelling or downwelling. This theory extends beyond the Ekman layer (the wind-driven surface layer) to describe the physical mechanisms beneath it, particularly in eastern boundary upwelling systems. Sverdrup's work is especially relevant in the context of Ekman pumping and nutrient cycling, as it links wind stress curl to Ekman transport, demonstrating how variations in wind patterns can induce vertical water movements and sustain upwelling systems. This Sverdrup's theory is based on the equation:

$$\beta V = \frac{1}{f} (\nabla \times \vec{\tau}) \quad (2.2)$$

Where βV is wind stress curl driven; $\nabla \times \vec{\tau}$ is wind stress curl; f is Coriolis parameter.

The limitations of this Sverdrup's theory are linear steady-state flow; neglects friction and inertial effects; and not directly applicable at coastal scale.

Henry Stommel (1948) built upon Sverdrup's theory introducing the concept of western intensification, explaining why ocean currents such as the Gulf Stream are stronger and narrower on the western side of ocean basins. His work focused on linear friction and the intensification of western boundary currents, demonstrating how the interaction between broader oceanic circulation patterns and coastal dynamics influences the persistence and variability of upwelling systems. Stommel's theory emphasizes gyre dynamics and western

boundary currents, showing that a combination of the Coriolis effect and the conservation of potential vorticity leads to this intensification. This concept is crucial for understanding heat and momentum transport in the ocean. The Stommel equation is summarised by the linear vorticity balance:

$$\beta v = (\nabla \times \vec{\tau}) - r \nabla^2 \psi \quad (2.3)$$

where r is the linear friction function; ψ is the streamfunction

Sverdrup's and Stommel's theories provide essential frameworks for understanding key aspects of the upwelling process, particularly the physical mechanisms driving large-scale ocean circulation and vertical water movements. The three theories Ekman, Sverdrup, and Stommel are interconnected. Ekman transport describes how surface winds drive ocean currents, leading to upwelling and downwelling. Sverdrup's theory explains how wind stress influences large-scale circulation and vertical water movement. Stommel's theory builds on this by explaining asymmetries in ocean gyres and the intensification of western boundary currents.

Together, these theories form a comprehensive foundation for understanding coastal upwelling processes. The following literature review is focused on physical mechanisms and drivers, impacts, trends and predictability of coastal upwelling in EBUSs, aligning with the present study's objectives.

2.2 Physical Mechanisms as Drivers of Coastal Upwelling Processes in EBUSs

The coastal ocean's response to atmospheric forcing is shaped by coastal jets, upwelling, and Kelvin waves, with wind stress curl playing a crucial role (Fennel, 1999). Several physical mechanisms were proposed for understanding the process behind the Northwest African and Gulf of Guinea coastal upwelling systems (Fig. 2.2), with wind-induced coastal divergence

being the most significant. These mechanisms can be categorized into local, remote, and large-scale factors.

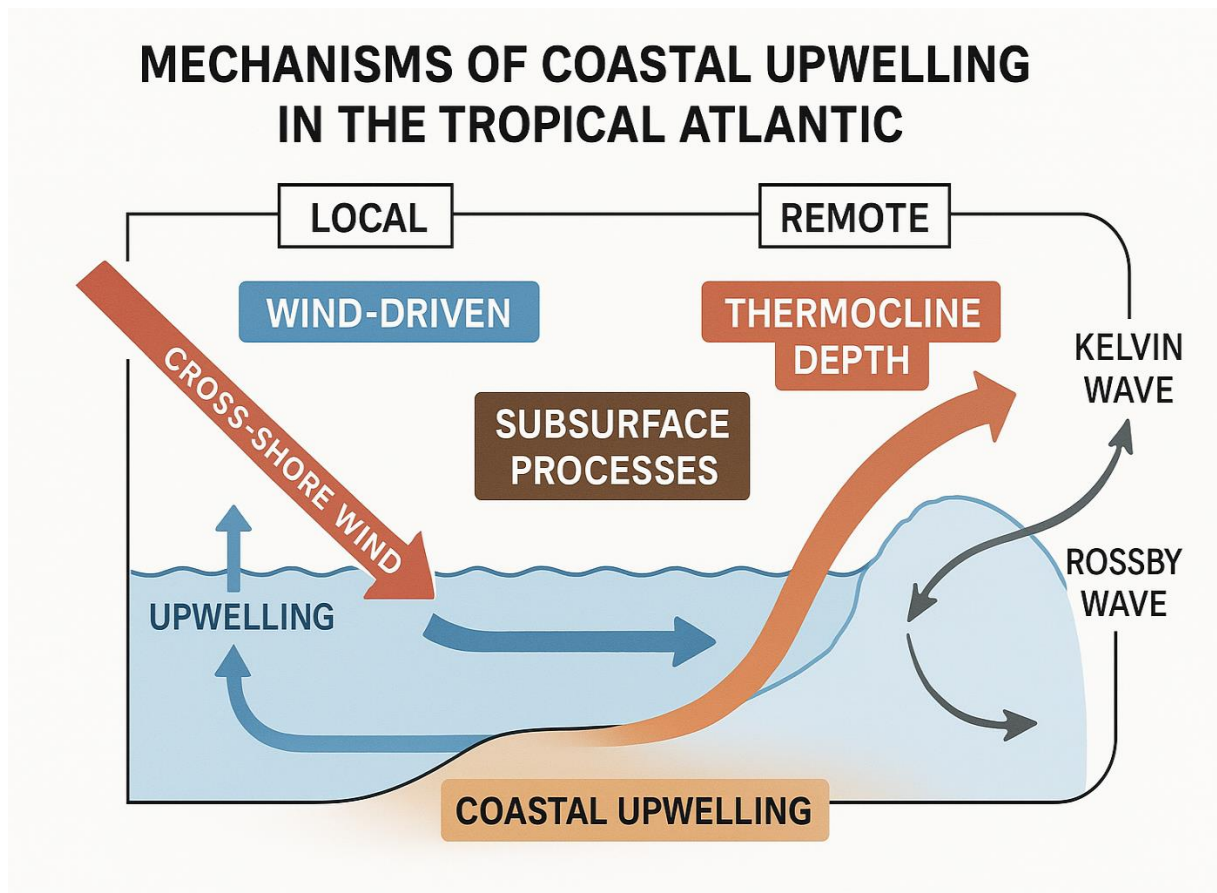


Figure 2.2: Summary on the physical mechanisms of coastal upwelling in the eastern Atlantic boundary upwelling system (Illustration by the author).

2.2.1 Local Mechanisms as Drivers of Coastal Upwelling

Previous studies (Brand *et al.* 2023) have shown that local mechanisms as drivers of coastal upwelling process, include the classic theory of wind stress-driven offshore Ekman transport developed in the EBUSs (Bakun 1975), wind stress curl driven Ekman pumping, local wind vorticity, bathymetry, coastal geometry and orientation and mesoscale eddies. Coastal trapped waves and coastline, and surface heat fluxes. Some of these factors such as wind stress driven Ekman dynamics and regional ocean currents were observed as primarily drivers of coastal in the EBUSs (e.g., Bakun, 1975; Colin, 1988).

2.2.1.1 Wind-driven Upwelling Theory

In the EBUSs such Benguela, California, Canary and Humboldt upwelling systems, the strength and seasonality of coastal upwelling are traditionally linked to the combined effects of wind-induced coastal divergence, with wind stress playing a crucial role generating Ekman dynamics such as offshore Ekman transport and vertical Ekman pumping, and the Coriolis force (Ekman 1905, Sverdrup 1947). Wind-driven Ekman transport moves surface waters away from the coast, creating divergence that promotes the upwelling of deeper, colder, nutrient-rich waters. Bakun (1975) expanded on the upwelling process, emphasizing the influence of seasonal and geographical variations in coastal upwelling. He highlighted that the strength and extent of upwelling can vary depending on wind patterns, topography, and other environmental factors.

In the eastern subtropical basins, where trade winds tend to slow down near the coast, studies found that the positive divergence of oceanic circulation may induce a cyclonic wind stress curl, contributing to upwelling (Marchal and Picaut, 1977; Binet 1997). In the recent studies, these effects of cyclonic eddies are associated with Ekman pumping (Capet *et al.*, 2004;

Bravo *et al.*, 2016; Desbiolles *et al.* 2016; Renault *et al.*, 2016). Both offshore Ekman transport and Ekman pumping enhance nutrient levels and lead to increased biological production along the coast (Pennington *et al.*, 2006; Bordbar *et al.*, 2021).

Regarding the Northwest African coast, several local mechanisms have been proposed to explain the upwelling process. Along the Senegal-Mauritania coast, upwelling is primarily associated to the seasonally of trade wind stress modulated by the Azores high-pressure system and the meridional migration of the ITCZ (Roy, 1989, Faye *et al.*, 2015). During boreal winter and spring, the southward migration of ITCZ due to the strengthening of the Azores high-pressure system enhances upwelling-favoring wind stress (equatorward trade winds) that drives offshore Ekman transport and wind-driven upwelling along the Senegal-Mauritania coasts (Benazzouz *et al.*, 2014; Ndoye *et al.*, 2014). Physical and hydrological analyses linked to thermohaline structures in the southern Senegal upwelling centre, revealed that upwelling is influenced by favourable winds and high complex interactions between coastal currents and mesoscale structures, such as by internal waves, intensive mixing processes and mesoscale eddies that modify thermohaline properties (Capet *et al.*, 2017).

In the North of Gulf of Guinea regions as the eastern equatorial, drivers and variability of upwelling remain unclear. Seasonal variations in wind forcing and equatorial dynamics combine to control thermocline depth and the onset of upwelling along the coast (Bakun, 1978; Philander, 1990). The link between SST and wind stress curl in the North Gulf of Guinea coast was first suggested by Katz and Garzoli (1982) and Garzoli and Katz (1983). Using a model of the tropical Atlantic, Philander and Pacanowski (1986) showed the influence of both winds and the wind stress curl on the Guinea coastal upwelling. Colin (1991) and Djakouré *et al.*, (2014) also highlighted Ekman pumping caused by wind stress curl and cape effects. However, the maximum in Ekman transport divergence in boreal summer does not coincide with the minimum in SST (Bakun, 1978).

Djakouré *et al.*, (2014, 2017) performed the sensitivity experiments in the tropical Atlantic regional ocean model system (ROMS), with an embedded high-resolution nest for the Gulf of Guinea, to identify the dominant processes driving the seasonal upwelling in the North of Gulf of Guinea. Their results distinguished two mechanisms: inertial detachment-induced upwelling east of Cape Palmas and wind-forced coastal divergence east of Cape Three Points. Wind-driven upwelling theory was performed to explain the presence of cold waters east of Cape Three Points. They found that a significant Ekman transport divergence can contribute to cooling east of Cape Three Points. Da-Allada *et al.*, (2021) supported these findings, showing that surface cooling at Cape Palmas is driven by zonal advection and increased turbulent mixing due to Guinea Current strengthening, while at Cape Three Points, upwelling is primarily wind-driven, intensified by stronger zonal wind stress and offshore Ekman transport. Recently, Illig *et al.*, (2024) found that changes in equatorial wind stress anomalies and ocean dynamics strongly influences of interannual variability in coastal upwelling systems.

In addition, the interannual variability analysis of the in-situ measurements of the sea surface temperature (SST) in the Gulf of Guinea (Sohou *et al.*, 2020) showed that upwelling is more pronounced in the west (Côte d'Ivoire and Ghana) than in the east (Benin and Nigeria). Caniaux *et al.*, (2011) suggested that the Gulf of Guinea upwelling is marked by the development of the equatorial cold tongue, but limited in the eastern edge by the Niger River plume (Alory *et al.*, 2021). For Alory *et al.*, (202) the Niger River-induced onshore geostrophic flow that weakens wind-driven coastal cooling near River mouth. While river discharge significantly modulates upwelling, reducing it by 50% and leads to a coastal warming of about 1°C near 2°E due to reduced turbulent mixing from enhanced salt stratification. This result indicates that Ekman transport alone cannot fully explain upwelling

variability, underscoring the need for further research on ocean-river interactions in a changing climate.

Further investigations in the tropical upwelling systems, in particular in the eastern Atlantic boundary upwelling systems, have shown that coastal upwelling is a complex system that cannot be explained by wind stress alone. In many tropical upwelling regions, ocean scientists (e.g., Brandt *et al.*, 2023; Körner *et al.*, 2024) found that peaks of wind stress and ecosystem productivity do not always align. As a result, other hypotheses beyond wind stress have been proposed to understand coastal upwelling in these regions. These hypotheses are based on role mesoscale eddies, the presence of capes, the role regional ocean currents, and other environmental factors.

2.2.1.2 Cape Effects and Contribution of Mesoscale Eddies

In the SMUS, the regional ocean model was performed by Ndoye *et al.*, (2014, 2017) and Capet *et al.*, (2017). Their results highlighted the role of the cross-shore geostrophic flow, mesoscale eddies, regional ocean currents and coastal topography including bathymetry, continental shelf and coastal shape, as local mechanisms that sustain upwelling along the Senegal-Mauritania coast. For them, the variations of eddies, bathymetry and coastal topography affect Ekman transport efficiency and allows more effective upwelling. The influence of mesoscale activity extends across the shelf break and far over the shelf, impacting the mid-shelf upwelling, possibly in concert with wind fluctuations (Capet *et al.*, 2017). Mesoscale instabilities and internal gravitational waves were therefore found to play a major role in mass transport and vertical mixing (Capet *et al.*, 2017).

Along the North of Gulf of Guinea coast, Bakun (1978) found that the maximum wind-driven velocity observed approximately 300 km east of the coldest surface waters, was possibly due to the influence of capes. Marchal and Picaut (1977) and Binet (1997) suggested

that spatial variations in wind intensity can create vorticity cells that modulate upwelling efficiency. They analysed isotherm displacements between Ghana and Côte d'Ivoire and found that vertical pumping associated with cyclonic eddies generated at the downstream of Capes Three Points and Palmas could explain the upwelling of cool waters. But this hypothesis was dined by results of regional ocean model performed by Djakouré *et al.*, (2014, 2017). They found that cyclonic eddies downstream of capes do not significantly contribute to Gulf of Guinea upwelling. Brandt *et al.*, (2011) suggested the presence of submesoscale activity (filaments and eddies) with a large modulating effect on wind-stress-curl-driven upwelling.

2.2.1.3 Role of Regional Ocean Currents

The interactions between regional ocean currents and coastline (Fig. 2.3) have observed as the local driver of coastal upwelling modulated by remote influences. Eastern boundary currents like the Canary Current off Northwest Africa (Pelegrí and Peña-Izquierdo, 2015; Benazzou *et al.*, 2015) and the Guinea current in the Gulf of Guinea (Colin, 1988; 1991; 1993; Djakouré *et al.*, 2014; 2017) influence SST variability and enhance coastal upwelling by reinforcing surface water divergence.

Recent studies in the Senegal-Mauritania upwelling region have shown that this upwelling is modulated by the Poleward current (Benazouzz *et al.*, 2014, Klenz *et al.*, 2018; Kounta *et al.*, 2018) and NECC (Faye *et al.*, 2015) that enhance stratification and shoaling thermocline. According to Klenz *et al.* (2018), the poleward current (PC) exhibits significant seasonal variability. During the upwelling season (December to April), the PC exists primarily as a subsurface poleward undercurrent beneath an equatorward coastal jet. During the Relaxation Season (May to July), the PC intensifies and surfaces, resulting in a strong poleward flow exceeding 30 cm/s from the surface down to 250 m depth. This surfacing is attributed to the weakening of alongshore, upwelling-favorable winds and a maximum in wind stress curl,

leading to adjustments in the eastern boundary circulation. The surfacing of the PC during the relaxation season can influence SST and upwelling dynamics in several ways such as advection warm water, nutrient supply modulation and the interaction with other currents. The surfaced PC and intensification can transport advection warmer waters poleward, alter the nutrient dynamics by modifying the vertical and horizontal distribution of nutrient-rich waters, impacting biological productivity, and interact with other oceanic features, NECC, influencing the overall circulation patterns and SST variability in the region.

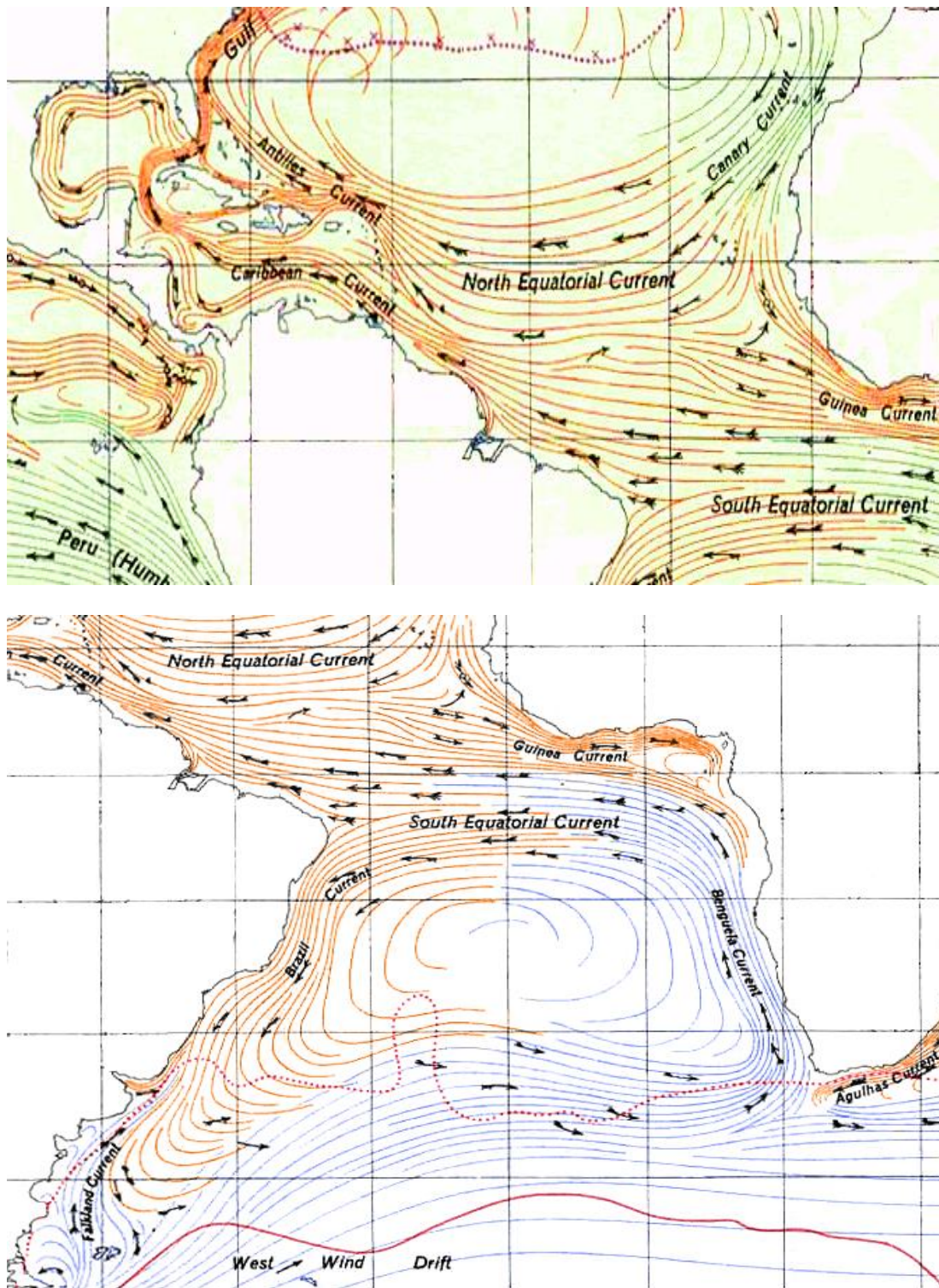


Figure 2.3: General Circulation of Ocean Currents in the Tropical Atlantic (Online source).

The results of Kounta *et al.*, (2018), reveals that the upper ocean circulation between approximately 8°N and 20°N is primarily poleward, driven by positive wind stress curl forcing. This variability is attributed to the influence of coastal trapped waves and Rossby wave dynamics.

In the Gulf of Guinea, coastal upwelling does not follow the classic offshore Ekman transport driven by wind stress, as observed along other EBUSs such as the Benguela, Humboldt, California, and Canary currents (Bakun, 1975). Coastal upwelling in the Gulf of Guinea was found as a complex system modulated by several mechanisms such as the seasonal interplay between Guinea current and coastal topography (Ingham, 1970; Philander, 1979) and NECC (Brandt *et al.*, 2011). Early studies (Colin, 1988; Colin *et al.*, 1991; 1993; Verstraete, 1992) linked coastal upwelling to the detachment of Guinea Current, driven by both local and remote wind forcing, which tilts the thermocline and brings cooler subsurface waters to the surface.

Based on FOCAL program measurements (1983-1984), Colin (1988) found that SST variability is closely linked to the inertia-driven of Guinea current's intensity and latitudinal extent. In boreal summer, offshore shifting of the Guinea Current raises the thermocline, enhanced by stronger alongshore winds, leading to the lowest SST values in July-August (Colin, 1988). Winter cooling over the shelf is also influenced by the Guinea current. East of Cape Palmas, upwelling is driven by the current's extension, nonlinear dynamics, and momentum advection, while this effect is weaker off Cape Three Points. Verstraete (1992) identified Gulf of Guinea upwelling as a large-scale phenomenon driven by the Guinea Current. He found that the strengthening of the cross-equatorial winds in summer intensify the Guinea Current, causing thermocline shoaling and enhancing upwelling via offshore Ekman drift.

Using the sensitive experiments in the regional ocean model, Djakouré *et al.*, (2017) ruled out capes and eddies as key drivers of upwelling (Marchal and Picaut, 1977; Binet, 1997) and reaffirming the role of Guinea Current suggested in the previous studies (Ingahm, 1970; Colin 1988; Verstraete, 1992). They demonstrated that cyclonic eddies generated at the downstream of capes do not significant contribution to Gulf of Guinea upwelling, which persists without capes but disappears when nonlinear momentum terms are removed. Instead, they highlighted the nonlinear dynamics of the Guinea Current as the primary driver, where its inertial detachment east of Cape Palmas leads to thermocline upwelling (Djakouré *et al.*, 2017).

Their findings also showed that vertical pumping in the western upwelling cell is mainly driven by momentum advection, while offshore Ekman transport dominates cooling in the eastern upwelling cell. Therefore, onshore geostrophic flow can partially compensate for wind-driven offshore transport, reducing upwelling in some regions (Marchesiello and Estrade, 2010; Rossi *et al.*, 2013).

Other upwelling contributors were observed in the Gulf of Guinea. The net surface heat budget including latent, sensible, and solar heat fluxes (Hormann and Brandt, 2009) and enhanced turbulent mixing in shallow waters near the coast (Brandt *et al.*, 2023) were found to modulate upwelling strength by controlling surface water cooling or warming.

Coastal upwelling is not only explained by the local factors. Remote and large-scale factors were also used to explain upwelling intensity and variability over seasonal, interannual, and decadal timescales.

2.2.2 Remote Forcing as Large-scale Drivers of Coastal Upwelling

The more documented remote forcing as large-scale drivers of EBUSs including the Northwest African and Gulf of Guinea coastal upwelling regions, are remote oceanic forcing

including equatorial Kelvin and Rossby waves, remote wind forcing, large-scale atmospheric and ocean circulations (ITCZ, subtropical high-pressure systems), large-scale climate modes and cross-basin teleconnections such as ENSO, North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Southern Oscillation Index (SOI), Pacific Decade Oscillation (PDO), Indian Ocean Dipole (IOD).

2.2.2.1 Equatorial Dynamic Theories

The equatorial dynamics, including equatorial Kelvin and Rossby waves, and coastal trapped waves (CTWs) are one of the important remote drivers of coastal upwelling. Studies have shown that Canary Current, part of the eastern limb of the North Atlantic subtropical gyres (Pelegrí and Peña-Izquierdo, 2015), interacts with wind-driven processes and equatorial currents guided by the eastward propagation of Kelvin waves (Polo *et al.*, 2008) to sustain the upwelling along the Northwest African coast.

These waves influence coastal sea level and subsurface temperature near the thermocline, with their role found to be dominant over local atmospheric forcing (Illig *et al.*, 2024). Studies have suggested that equatorial waves can affect SST variability in coastal upwelling systems, highlighting the long-range impact of large-scale climatic drivers (Picaut, 1983; Illig *et al.*, 2024).

Most of eastern Atlantic boundary upwelling systems, such as Angola-Benguela and North of the Gulf of Guinea current systems were primarily associated to coastal trapped waves (Bachelery *et al.*, 2016; Brandt *et al.*, 2023; Körner *et al.*, 2024) generated by the eastern propagation of Kelvin waves (Polo *et al.*, 2008), and the interactions of regional ocean currents with coastline influenced by seasonal remote forcing from equatorial Kelvin and Rossby waves.

The waves propagate from the equator to the coast, inducing upwelling via their influence on sea level and thermocline depth (Moore *et al.*, 1978; Bah, 1980; Picaut, 1983). The

propagation of Kelvin waves in the eastern Atlantic increase the easterly wind in the western equatorial Atlantic and creates an internal upwelling Kelvin waves that propagate eastward along the equator. When they reach the African coast, these waves reflect as coastal Kelvin waves that moves along the coast (Polo *et al.*, 2008).

The GoG coastal upwelling system is suggested to be controlled by remote forcing via equatorial Kelvin and coastal trapped waves (Moore *et al.*, 1978; Philander, 1979; Servain *et al.*, 1982; Clarke, 1983; Illig *et al.*, 2024), Rossby-gravity waves (Clarke, 1979; Weisberg *et al.*, 1979). The interaction between equatorial Kelvin waves and coastal topography causes a reflected coastal Kelvin wave that propagates along the coast, contributing to upwelling in the Gulf of Guinea and other tropical upwelling systems (Philander, 1990; Picaut, 1983; Illig *et al.*, 2024). Results of Bah (1980) have shown that upwelling in the oceanic equatorial region is due to the eastward propagating equatorially trapped Kelvin waves, while the coastal upwelling is due to the westward propagating reflected Rossby waves and to the poleward propagating Kelvin wave. He found that the sudden onset and duration (about 90 days after the onset) of wind stress in the western Atlantic Ocean, can excite wind induced equatorially trapped Kelvin waves which generate equatorial and coastal upwelling on their way eastwards. The role of the non-rectilinear coast was clearly associated to Kelvin wave effects. The intense upwelling was observed in the east than west of the main capes Palmas and Three Points with a maximum upwelling located the east of Cape Three Points due to the influence of non-rectilinear coastline (Bah 1980). Further elements were presented in support of coastal wave propagation in the Tropical Atlantic with SST (Picaut, 1983).

Recent findings from high-resolution tropical Atlantic Ocean model experiments (Illig *et al.*, 2004) found that winds at the equator generate equatorial Kelvin waves that continue to propagate along the equator and further south- and northward over thousands of kilometers extending as far as 10°–15° latitude along the African coastline as CTWs (Polo *et al.*, 20208)

and produce thermocline displacements along the eastern boundary. These results highlight the strong contribution of both equatorially-forced CTWs and reflected equatorial Rossby waves to the coastal variability along the shelf.

Exploring the oceanic connection between the equatorial dynamics and the coastal variability along the northern coast of the Gulf of Guinea over 1958-2015, Illig *et al.*, (2024) found that Equatorial Kelvin waves forced by wind-stress anomalies in the west-central equatorial basin, significantly control the interannual fluctuations of the coastal sea-level and subsurface temperature near the thermocline (>70%), leaving only a marginal role for the local atmospheric forcing. They found that the remote equatorial forcing explains a significant portion of SST variability in coastal upwelling systems. They reported that the surface forcing in the eastern Atlantic and along the North of the Gulf of Guinea coast tends to accelerate the coastal propagations by 10%–20% during its phase-speed. These results open the possibility of predicting interannual changes in coastal conditions off West African coasts, a few months in advance.

Some results have concluded no evidence of the direct of Kelvin waves on the seasonal upwelling along the Equator from the western Atlantic (Clarke, 1979; Weisberg *et al.*, 1979). They found that a significant part of the incident equatorial energy is transmitted poleward along the west African coast as Coastal Trapped Waves (Clarke, 1983). Rossby Waves influence the thermocline depth, affecting upwelling intensity over longer timescales. Hormann and Brandt (2009) particularly studied the amplitude of equatorial Kelvin waves and found a minor direct impact on boreal summer SST variability. Compared to the exceptionally strong wave activity in 2002 and 2005, they found that equatorial Kelvin waves were generally weaker during 2005. Philander and Pacanowski (1986) also evaluated the hypothesis linking equatorial variability to the seasonal cooling of the Gulf of Guinea coastal SST (Picaut, 1983), using a general circulation model and found no evidence of

coastal trapping. Challenging the idea that coastal upwelling is primarily driven by poleward-propagating coastal trapped waves, this finding aligns with Philander and Pacanowski's (1981) model analysis, based on the simplified ocean motion equation. Verstraete (1992) tested the remote forcing theory and suggests that equatorial dynamics govern not just seasonal cycles but also quasi-El Niño events, but this mechanism remains uncertain (Djakouré *et al.*, 2017).

The mechanism based on equatorial dynamics and the turbulent mixing, was also tested in other tropical Atlantic upwelling systems (Körner *et al.*, 2023, Brandt *et al.*, 2024). In the Benguela upwelling system, interannual remotely-forced CTW induce strong meridional and vertical currents anomalies along the slope of the continental shelf (Bachèlery *et al.*, 2020). In this region, the CTWs generated at the eastern boundary by the impinging EKW were associated with the SST anomalies (Imbol Koungue *et al.*, 2021). Off Angola, Imbol Koungue *et al.*, (2021) found that ocean dynamics at intraseasonal time scale have been evidenced to impact SST variability along the southwestern African coast and in the Gulf of Guinea. In the tropical Angola upwelling system, Körner *et al.*, (2023) reported that the seasonal maxima of productivity occur when upwelling favourable winds are weak. They found that this coastal upwelling can be mainly controlled by the combined effect of coastal trapped waves (CTWs) and elevated tidal mixing on the shelf and the wind forcing plays only a secondary role (Körner *et al.*, 2024). However, the north and south of Benguela upwelling system were found to be forced by alongshore winds and offshore cyclonic wind stress curl (Brandt *et al.*, 2024). It has found worth noting that the thermocline depth, the strength of the coastal current and thus the upwelling, are all under the seasonal remote influence of the equatorial ocean through the propagation of equatorial Kelvin and Rossby waves and also of CTWs.

The seasonal migration of Intertropical ITCZ affects trade winds, influencing the intensity of coastal upwelling. Subtropical high-pressure systems such as the position and strength of the Azores High (North Atlantic) or St. Helena High (South Atlantic) regulate wind patterns that drive upwelling. The Gulf Guinea cooling develops when the equatorial cold tongue reaches its peak in July–August and August–September in the Atlantic and eastern Pacific, respectively (Okumura and Xie, 2004). Studying the air–sea interactions in the Gulf of Guinea during boreal spring and summer, Coëtlogon *et al.*, (2010) suggested that intraseasonal variability in the Gulf of Guinea is connected to large-scale fluctuations in the South Atlantic. They found that the surface wind-stress variability explains 20% of the total variance of SST and corresponds to stronger or weaker southeasterlies over most of the Gulf of Guinea.

The interannual variability in upwelling, is influenced by large-scale atmospheric forcing and oceanic responses (ENSO, NAO). The fluctuations of local alongshore winds (Richter *et al.* 2010) and other local processes such as freshwater inputs (Alory *et al.*, 2021) further generate SST anomalies in the tropical upwelling systems.

2.2.2.2 Influence of Large-scale Climate Drivers

The interannual variabilities such as ENSO, NAO, AMO and other teleconnections such as IOD, Pacific PDO, thermocline depth and large-scale climate patterns (ITCZ, subtropical high-pressure systems) are the large-scale factors that modulate coastal upwelling in the EBUSs (Lübbecke *et al.*, 2019; Yu *et al.*, 2020; Wade *et al.*, 2023). The relationships between upwelling systems and Pacific ENSO were established in the EBUSs, such as CalUS (Bograd *et al.*, 2009), Benguela-Angola upwelling system, HUS and CanUS (Imbol Koungue *et al.* 2019). For example, El Niño and negative NAO weaken trade winds, reducing or suppressing upwelling and leading to warmer SSTs, while La Niña and positive NAO strengthen trade winds, enhancing upwelling and cooling SSTs.

El Niño events also generate downwelling (upwelling) Kelvin waves that propagate along the equator and then poleward along the African coast, suppressing upwelling. During La Niña, upwelling-favorable Kelvin waves can strengthen cold anomalies. Philander (1979) noted similarities between coastal upwelling process and El Niño in the Pacific. In the Atlantic, warm (Niño) and cold (Niña) anomalies which is peaks during June–July (Keenlyside and Latif, 2007; Lübbecke *et al.*, 2018, Nnamchi *et al.*, 2021), are also associated with SSS variability (Awo *et al.* 2018) and anomalous deep thermocline and correspondingly reduce or enhance upwelling along the West African coasts, respectively (Lübbecke *et al.*, 2018). During an Atlantic Niño, the southward shift of the ITCZ brings maximum rainfall in the eastern tropical Atlantic and potentially increases the flow of surrounding rivers, affecting near-surface stratification (Awo *et al.*, 2018).

In the SMUS, the potential drivers of upwelling interannual variability are similar to drivers of seasonal changes. They include changes in the wind forcing, turbulent mixing and remote forcing (Wade *et al.*, 2011) associated with the climate variability mode. For Oettli *et al.*, (2016), the interannual variability of the regional mixed-layer temperature anomaly that evolves in boreal late fall and peaks in spring is associated with the alongshore wind anomaly, mixed-layer depth anomaly and cross-shore atmospheric pressure gradient anomaly. Koseki *et al.*, (2024) investigated the future change of Dakar Niño under the highest emission scenario of CMIP5. Comparing the Dakar Niño variability between the 1980-2010 and 2069-2099 periods, they found that its variability is more intense during the coldest (Niña) than during the warmest (Niños) SST event; and the ocean temperature variability is connected more deeply with the Dakar Niño variability.

Wade *et al.* (2023) have recently found a teleconnection between ENSO and Senegal coastal upwelling variability. They showed that the Atlantic multidecadal variability (AMV) influence El Nino and La Nina and local SSTs and associated drivers over Senegal coastal

upwelling. They also suggested that the AMV and other processes such as horizontal advection may control the Senegal coastal upwelling SSTs, acting as a modulator for the ENSO and Senegal coastal upwelling teleconnection. They found that during decades in which the North Atlantic is colder than the South Atlantic, ENSO teleconnection over the upwelling in the Senegal coastal upwelling region is stronger. However, no teleconnection between anomalous local Ekman transport and ENSO. Local indices of the mixed layer heat budget during the intense upwelling season exhibit pronounced interannual to decadal variability. Ndoye *et al.*, (2014) found large uncertainties in the south Senegal coastal upwelling diurnal heat budget. They suggested that coastal upwelling intensity varies depending on several factors, wind intensity, topography, Coriolis parameter, and strongly modulated by meso-submesoscale activity.

In the Gulf of Guinea, the prevailing dynamic of Atlantic Niño (Brandt *et al.*, 2011; Nnamchi *et al.*, 2015; 2016; Richter *et al.*, 2013; Martín-Rey *et al.*, 2019) has long been known to have a remote impact on seasonal-to-interannual SST variability. This interannual variability is generally stronger in regions of strong seasonal variability (Wiafe and Nyadjro, 2015; Sohoun *et al.*, 2020). It has been shown that the coastal interannual variability in the Gulf of Guinea and Atlantic Niño and Niña events are significantly related with the equatorial activity (Lübbecke *et al.*, 2010; Imbol Koungue *et al.*, 2017). Using satellite-era observations from 1982–2015, Nnamchi *et al.*, (2021) show that diabatic heating variability associated with the seasonal migration of the ITCZ controls the seasonality of this Niño. Because the Gulf of Guinea system is closest to this Niño box, weak wind stress curl change and warm advection in the equatorial region is likely to affect upwelling (Chang *et al.*, 2024).

Schwing *et al.*, (2006) found no consistently strong relationship between upwelling and large-scale climate indices. For them, although El Niño events can weaken coastal upwelling, they are not the sole cause. Changes in biological productivity and geochemical

factors, such as nitrate concentration and dissolved oxygen, are closely tied to upwelling intensity and timing.

Schwing *et al.*, (2006) highlighted the strong impact of the 1997/1998 and 2015/2016 El Niño events and marine heatwaves on chlorophyll-a (Chl-a) concentrations. Kahru *et al.*, (2018) correlated Chl-a variability during these warm events with SST frequency. Trends indicate stronger upwelling winds during winter and the upwelling season between 35°N and 45°N, while southern regions show mixed results, with some areas experiencing reduced upwelling winds. The coastal upwelling index (CUI) tends to be strong during La Niña conditions, such as in 1998–1999 and 2010–2011, while minima in CUI align with strong ENSO events, including 1997/1998, 2009/2010, and 2015/2016. Chavez *et al.*, (2011) reported that the 1997–1998 ENSO anomaly significantly reduced primary productivity along the California coast due to decreased nutrient input.

A positive SOI can weaken the West African monsoon, reducing trade winds and weakening upwelling. A positive PDO phase (warmer Pacific SSTs) is often associated with weaker Atlantic trade winds and reduced upwelling. Global Warming and climate change increase surface heating and changes in wind patterns that may stratify the upper ocean and alter the strength and position of subtropical high-pressure systems affecting upwelling regions by reducing the efficiency of upwelling.

2.2.2.3 Coastal Upwelling Response to Global Warming and Climate Change Effects

Many studies have explored EBUSs responses to global warming and anthropogenic climate change using historical data and Intergovernmental Panel on Climate Change (IPCC) climate model projections (Bakun, 1990, Sydman *et al.*, 2014; Benazouzz *et al.*, 2015; Sylla *et al.*, 2019; Varela *et al.*, 2022). Findings indicate that climate change alters wind fields, leading to shifts in wind-driven upwelling, increased stratification, acidification, and ocean

deoxygenation (Gruber *et al.*, 2011; Bakun *et al.*, 2015). These changes are predicted to be particularly pronounced in tropical oceans, impacting subduction, upwelling, and air-sea gas exchange. These processes contribute to acidification, deoxygenation, and ecosystem disruptions (Bakun *et al.*, 2015). This Bakun's hypothesis remains central to understanding the link between oceanography, climate change, and marine ecosystems.

Previous studies (Varela *et al.*, 2021) have also shown that coastal upwelling can be modulated by the occurrence of extreme SST events so called MHWs, caused by the unusually ENSO, NAO, SOI and PDO (Oliver *et al.*, 2018; Holbrook *et al.*, 2019; Sen Gupta *et al.*, 2020) on the oceanic and coastal dynamics.

Many studies have found that these MHWs modulate the upwelling intensity and upper-ocean mixing thereby setting the upward supply of nutrients and drive significant impacts on coastal ecosystems (Pearce and Feng 2013; Frolicher *et al.*, 2018; Oliver *et al.*, 2021; Smale *et al.*, 2019; Brodeur *et al.*, 2019; Smith *et al.*, 2019; Belkin and Short 2023), with subsequent socio-economic consequences (Oliver *et al.*, 2021). They strongly influence marine life by shifting coastal ecosystem productivity (Frolicher and Laufkotter 2018; Frolicher *et al.*, 2018; Oliver *et al.*, 2018; Guo *et al.*, 2022), destroy marine coastal habitats including coral reefs, kelp forests (Thomsen *et al.*, 2019; Babcock *et al.*, 2019; Brodeur *et al.*, 2019; Benthuisen *et al.*, 2020), mangroves and marine protected areas (Smith *et al.*, 2023). The greatest impacts of these changes are expected in the tropical (Gulev *et al.*, 2021), in particular in the coastal upwelling regions (Oliver *et al.*, 2019; 2021) because of their fragility.

Despite of numerous local, remote and large-scale factors proposed to explain mechanisms and processes of coastal upwelling, the predictability of upwelling remain a challenge over West African coasts. In response to this literature review, the presence study proposes to

revise characteristics of coastal upwelling and to assess impacts of the extreme SST events on the upwelling dynamics and ecosystem productivity along Northwest African coasts.

The impact of climate change on upwelling ecosystems has been widely studied. The implications of Bakun's hypothesis highlight both biological impacts and potential risks. Bakun *et al.*, (2015) predicted that climate change-driven alterations in the intensity, spatial extent, frequency, and duration of upwelling will directly affect the physiology, metabolism, growth, and reproductive capacity of phytoplankton, zooplankton, and marine life. The greatest risk for many fish species may occur during larval and juvenile stages, where survival and recruitment depend on sufficient planktonic food resources. More intense upwelling could also increase hypoxic zones and exacerbate ocean acidification as CO₂-rich deep waters rise to the surface, potentially disrupting food chains, harming biodiversity, and altering fish stocks.

2.3 Socio-economic and Environmental Impacts of Coastal Upwelling

Coastal upwelling systems in the EBUSs are of significant environmental and socio-economic considerations, attracting widespread scientific attention. The Northwest African and Gulf of Guinea coastal upwelling regions are the eastern Atlantic boundary upwelling systems that play a crucial role in physical climate dynamics, marine biogeochemistry, and ecosystems. Numerous studies have documented their impacts on nutrient supply, biological productivity, local weather patterns, regional climate variability, fisheries, and socio-economic development (Amemou *et al.* 2020, Koné *et al.* 2017).

2.3.1 Biological and Socio-Economic Impacts of Coastal Upwelling

Coastal upwelling influences primary production, pelagic fish habitats, and marine resource abundance (Binet and Marchal, 1993; Binet and Servain, 1993). EBUSs contribute disproportionately to global ocean productivity, providing essential ecosystem services to

human society (Bograd *et al.*, 2023). Studies indicate that the recruitment and abundance of pelagic fish in EBUSs can be either positively or negatively related to upwelling intensity.

The spatial and temporal variability of nutrient-rich upwelled waters is primarily controlled by surface winds, with differences in alongshore winds driving coastal upwelling and local wind stress curl influencing offshore upwelling (Brandt *et al.*, 2011). A comparative study of surface thermal fields and pelagic fish density on the Senegalese continental shelf during the cold season revealed that the highest fish densities were concentrated in the coldest upwelling zones and along the periphery of the upwelling system (Demarcq and Samb, 1991). Off the coast of Senegal, Roy and Kifani (1989) found that recruitment success of pelagic fish fluctuates with upwelling intensity.

Menna *et al.*, (2015) reported that Chlorophyll-a (Chl-a) concentrations in the southern sector of the Northwest African upwelling system exhibit strong seasonal variations, peaking during the core upwelling season (December to June). They also demonstrated that fluctuations in wind forcing directly impact ocean conditions and ecosystem responses without significant time lag, with Chl-a increasing from October to May before declining in late spring. Similarly, Diankha *et al.*, (2015) established a strong link between *Ethmalosa fimbriata* abundance, SST, and phytoplankton biomass, showing that an increase in SST combined with a decrease in phytoplankton results in lower fish abundance.

The northern Gulf of Guinea is strongly influenced by coastal upwelling, which affects regional climate and fisheries (Bakun, 1978). Coastal upwelling plays a crucial role in primary production and supports fisheries with significant socio-economic benefits for bordering countries (Koné *et al.*, 2017; Amemou *et al.*, 2020).

However, changes in productivity are not always directly linked to upwelling intensity. For example, Kim *et al.*, (2009) and Nezlin *et al.*, (2018) found that phytoplankton blooms along

the California coast were not solely driven by upwelling but rather by the interaction between nutrient enrichment from upwelling and nutrient depletion caused by winter mixing, both influenced by climatic oscillations. Additionally, Howard *et al.*, (2017) identified anthropogenic nutrient inputs identified as significant contributors to nearshore productivity. The intensification of upwelling-favorable winds due to global warming and climate change (Bakun, 1990) may enhance marine productivity by increasing nutrient supply to the euphotic layer. However, stronger upwelling can also have negative effects, such as transporting plankton offshore or disrupting trophic interactions (Bakun *et al.*, 2015). During 2000-2001, Bode *et al.*, (2021) observed that reduced upwelling and increased precipitation favored zooplankton abundance.

2.3.2 Impacts of Coastal Upwelling on Local Weather and Regional Climate

SST anomalies are strongly correlated with summer rainfall in the Sahel and the coastal regions facing the Gulf of Guinea (Lamb, 1978). Equatorial cooling intensifies the southerly monsoon driven by the Saint Helena anticyclone in the Gulf of Guinea, pushing the continental rainband inland from the Guinean coast (Caniaux *et al.*, 2011). In response to monsoon onset, upwelling-induced cooling is most pronounced in the east due to both the strong acceleration of southerly winds and the shallow thermocline. Accelerated easterlies further enhance equatorial cooling by inducing upwelling and shoaling the thermocline in the east.

Equatorial ocean dynamics significantly influence the onset and amplitude of the African monsoon (Okumura and Xie, 2004; Caniaux *et al.*, 2011) and affect regional precipitation patterns (Lamb 1978; Fontaine and Janicot, 1992; Brandt *et al.*, 2011, Rodríguez-Fonseca *et al.*, 2015).

Numerous studies (de Coëtlogon *et al.* 2023; Kouadio *et al.*, 2013) have linked the seasonal cooling of the northern Gulf of Guinea (coastal upwelling) to the West African Monsoon (WAM) system. Using atmospheric general circulation model simulations, Okumura and Xie (2004) identified three key mechanisms driving easterly wind acceleration in the equatorial Atlantic during boreal summer, and which contribute to rapid oceanic cooling and feedback onto the African monsoon: the monsoon rainfall distribution induces zonal sea-level pressure gradients, generating easterly anomalies in the eastern Atlantic; strong cross-equatorial southerlies transport easterly momentum from the Southern Hemisphere to the equator; zonal pressure gradients linked to equatorial ocean cooling accelerate surface easterlies in the central and western Atlantic. According to Okumura and Xie (2004), the seasonal cycle of equatorial Atlantic SST is characterized by rapid cooling from April to July, coinciding with WAM onset. They argue that Atlantic Cold Tongue (ACT) cooling is primarily driven by the acceleration of southerly winds along the pressure gradient, induced by the heating of the West African continent. The upwelling-driven cooling is strongest in the Eastern Equatorial Atlantic (EEA), where southerly winds intensify and the thermocline is shallower. The cessation of coastal rainfall in early July appears to coincide with the emergence of upwelling along the Guinea Coast (de Coëtlogon *et al.*, 2014). Brandt *et al.*, (2010, 2011) showed that cold tongue SST anomalies influence the wind field in the Gulf of Guinea, driving the northward migration of humidity and convection, potentially triggering the WAM jump.

The seasonal cooling of the equatorial cold tongue is primarily driven by increased wind stress, enhanced surface heat fluxes, and vertical oceanic mixing (Peter *et al.*, 2006; Caniaux *et al.*, 2011). In the Gulf of Guinea, Caniaux *et al.*, (2011) attributed the wind increase mainly to the St. Helena anticyclone, reinforced by local wind variations due to surface heat flux gradients associated with the equatorial front in the EEA. They observed strong interactions

between the ACT and wind patterns over the EEA were observed, with a close correlation between the timing of ACT formation and the WAM jump, and suggested that the ACT plays a key role in the onset of the WAM. Late ACT and WAM onsets were associated with anomalously warm SSTs in the EEA, affecting regional climate and WAM onset, leading to either flooding or drought in neighboring countries (Imbol Koungue *et al.*, 2021). Low-level atmospheric divergence north of the equator reduces convection over the Gulf of Guinea, enhancing northward winds that shift convection over land.

Studying the surface wind response to SST in the Gulf of Guinea, Coëtlogon *et al.*, (2014) found that intraseasonal fluctuations of surface winds are strongly controlled by SST. This northward migration, in turn, strengthens subtropical trade winds in the southern tropics, intensifying coastal upwellings and inducing strong SST cooling in the ACT and Gulf of Guinea during boreal spring and summer.

Upwelling in the Gulf of Guinea significantly affects rainfall distribution along the West African coast and sub-Saharan regions (Lamb, 1978). SST variability is thought to modulate the amplitude of the African monsoon, influencing regional climate (Caniaux *et al.*, 2011). Martín-Rey *et al.*, (2019) highlighted the role of SST variability in shaping precipitation patterns before the WAM onset. Alory *et al.*, (2021) demonstrated that the seasonal development of the equatorial cold tongue contributes to the abrupt onset of the southerly monsoon in the Gulf of Guinea and the northward shift of the monsoon rainband over West Africa. They also found that the monsoon, in turn, strongly influences the seasonal evolution of the cold tongue through cross-equatorial southeasterly winds.

Recently, Coëtlogon *et al.*, (2023) investigated the mechanisms by which the GGUS influences precipitation using numerical simulations with the Weather Research and Forecasting (WRF) model. Their findings confirm that coastal upwelling weakens northward

humidity transport, reducing coastal humidity convergence and inhibiting deep convection. They found that the coastal upwelling feedback on atmospheric dynamics operates as follows: cooling of coastal SST slows the monsoon flow near the coast, reducing coastal humidity convergence, which inhibits deep convection and precipitation. They demonstrated that stronger (weaker) upwelling leads to a 20–30% decrease (increase) in coastal precipitation, explaining why the emergence of the Guinea Coast upwelling often marks the onset of the little dry season in July. Additionally, Coëtlogon *et al.*, (2023) showed that coastal upwelling weakens peak coastal precipitation by reducing the land-sea temperature gradient at night, leading to a weaker land breeze. They also showed that the intensity of coastal upwelling affects the diurnal distribution cycle of atmospheric pollutants by weakening their northeastern transport in the monsoon flow, particularly during the "moist morning" period-stronger upwelling limits inland transport, whereas weaker upwelling enhances it. Because of the influence of coastal upwelling, the predictability of WAM onset and strength in relation to SST patterns remains an open question.

2.4 Trends and Predictability of Coastal Upwelling

The near-surface ocean has undergone significant changes in recent decades, with global SST increasing by 1.5°C (Gulev *et al.*, 2011). Beyond global climate warming, Bakun (1990) hypothesized that rising greenhouse gas concentrations would intensify the ocean-land thermal gradient, strengthening upwelling-favorable winds and enhancing upwelling in EBUSs. These changes driven by anthropogenic CO₂ emissions and resulting climate shifts (Gruber *et al.*, 2021) would lead to extreme ocean events such as low oxygen concentrations, high acidity and MHW events, affecting marine organisms and carbonate structures (Bakun *et al.*, 2015). This Bakun's hypothesis has motivated numerous studies on the upwelling trends using in situ and remote observations, historical reanalysis, and climate model outputs. Some studies supported this hypothesis, finding a strong relationship between land-

sea temperature gradients and upwelling intensity in the 21st century (Seydman *et al.* 2014; Wang *et al.*, 2015).

Due to ongoing debate around this Bakun hypothesis, Sydman *et al.*, (2014) conducted a meta-analysis on the impact of climate change on upwelling winds at higher latitudes. They identified a general increase in upwelling-favorable winds in most systems (California, Benguela, and Humboldt) but not in the Canary system, where a greater likelihood of weakening was observed. Analyzing SST trends in the Canary Current Large Marine Ecosystem from 1982 to 2013, Vélez-Belchí *et al.*, (2015) reported a warming rate of 0.28°C per decade, with stronger warming in downwelling oceanic regions (0.5°C) than in coastal upwelling regions (0.25°C).

Aguirre *et al.* (2019) found consistent poleward shifts in migratory anticyclones over the North Atlantic and Southern Hemisphere, influencing upwelling systems. In the Canary, Humboldt, and Benguela systems, these shifts contribute to more frequent short-lived but intense upwelling-favorable wind events, suggesting a poleward shift of lower-level jets in the Canary and Humboldt systems. Three of the four major EBUSs are projected to experience more frequent strong upwelling events.

Studies have shown that coastal upwelling responses to the ongoing climate change differently. Changes in upwelling intensity, frequency and duration in the EBUSs are strongly linked to global warming due to the anthropogenic rise in atmospheric CO₂ and the resulting alterations in weather and climate patterns (Gruber *et al.*, 2021; Bograd *et al.*, 2023). Changes in regional climate have been found to affect wind regimes and currents, often cited as key drivers of long-term variability (Bode *et al.*, 2021). Large-scale climate forcing influences local weather patterns and upwelling intensity by modifying wind conditions. However, no consistent relationship has been observed between rising water

temperatures, nutrient variability, and atmospheric pressure changes. The southern displacement of high pressure over the North Atlantic, associated with negative NAO phases (Barnston and Livezey 1987), has been suggested as a factor. Nevertheless, Bode *et al.*, (2009, 2011) indicated that climate indices do not necessarily translate into direct changes in upwelling.

Kessler *et al.*, (2022) analyzed Atlantic Large Marine Ecosystems (LMEs) and found no systematic changes in seasonal SST amplitude. However, they observed that North Atlantic LMEs are warming faster than those in the South Atlantic, with the gap increasing over time.

Climate models often exhibit biases in mean-state and variability for the upwelling regions (Li *et al.*, 2020; Richter *et al.*, 2015; Richter and Tokinaga, 2020). Most of climate models predict the poleward shift of upwelling in EBUSs.

Long-term trends in EBUS are linked to anthropogenic influences and predictable shifts in large-scale atmospheric pressure systems (Rykacewski *et al.*, 2015). Ecosystem variations are expected in response to shifts in upwelling wind intensity, offshore advection, and thermocline depth (Bakun, 1990; Bakun *et al.*, 2015). Additionally, human activities may contribute to long-term alterations in upwelling dynamics, particularly in upwelling-favorable winds (Bakun, 1990). Global ocean acidification is profoundly impacting coastal waters, disrupting the trophic chain, net primary production, and fisheries (Bakun *et al.*, 2015).

The multiannual variability of plankton production was expected to be linked to ENSO in the Pacific EBUS (Chavez *et al.*, 2011). However, Bode *et al.*, (2011) found non-linear interactions between phytoplankton and climate, with no significant long-term trend in biomass, despite lagged relationships between external factors and phytoplankton production. They demonstrated that upwelling winds and variations in source water origins

do not fully explain multidecadal variability in chlorophyll-a and primary productivity in upwelling regions. Other factors, such as changes in near-surface stratification, turbulent diffusion rates, and thermocline depth associated with large-scale climate events, may also play a role (Bakun *et al.*, 2015). These shifts are expected to impact pelagic fish resources and may lead to a transition toward more subtropical community compositions.

Studies have also examined potential climate change impacts on productivity and fisheries in the Gulf of Guinea by the end of the 21st century. According to Xiu *et al.*, (2018), climate change will intensify upwelling in the California Current system due to stronger alongshore winds and enhanced upper-ocean stratification in both coastal and open-ocean regions. Open-ocean warming is expected to increase deep nutrient concentrations, enhancing nutrient fluxes to source waters. Increased winds and eddy activity may further facilitate upward nutrient transport to the euphotic zone. However, plankton communities may exhibit complex, nonlinear responses to increased nutrient input due to intricate food web interactions.

Siemer *et al.*, (2021) analyzed trends in SST, chlorophyll-a, net primary production (NPP), and meridional wind stress in the Eastern North Atlantic subtropical gyre to assess global trends in open-ocean and upwelling regions. They observed significant warming, with a peak of 2.7°C per century in the Azores, and a general decline in chlorophyll-a and NPP, particularly in permanent upwelling zones, contributing to a 0.13% global NPP loss per century. While increased meridional wind stress aligns with theoretical expectations, it contrasts with observed declines in chlorophyll-a and NPP in upwelling regions. In some areas, stronger upwelling winds lead to surface cooling and increased productivity. However, warming in both open-ocean and upwelling zones better explains declines in productivity than wind stress changes alone. Factors such as stratification and coastal trapped

waves, which were overlooked in Bakun's hypothesis, may limit nutrient exchange and regulate upwelling intensity through wind stress-stratification interactions.

Bograd *et al.*, (2023) examined climate change impacts on EBUSs from a biogeochemical perspective. They reported enhanced coastal stratification, poleward displacement of subtropical highs, stronger alongshore wind stress and wind stress curl, upwelling intensification in some regions, longer upwelling seasons in the Humboldt, Canary, and Benguela systems, deoxygenation and higher nutrient content in the California and Humboldt systems, increased offshore phytoplankton transport in the Canary and Benguela systems, and nonlinear or uncertain productivity responses. However, results varied by EBUS, natural climate fluctuations, wind datasets, time periods, methodologies, and statistical tests.

Bakun's proposed mechanism has been challenged by several studies using high-resolution data and regional models (Benazouzz *et al.*, 2015; Wang *et al.*, 2015; 2023; Rykaczewski *et al.*, 2015). Some studies suggest that coastal upwelling can increase or decrease independently of anthropogenic climate change due to rising greenhouse gases.

Using an ensemble of climate models, Wang *et al.*, (2015) found significant and consistent changes in the timing, intensity, and spatial variability of coastal upwelling under future warming across most EBUSs. They linked these changes to increasing summertime land-sea temperature differences, which intensify upwelling-favorable winds. However, their analysis focused only on latitudes where these trends were statistically significant. Wang *et al.*, (2015) also explored the relationship between thermal gradients and offshore Ekman transport under greenhouse gas scenarios, predicting stronger upwelling winds by the late 21st century in the Canary, Humboldt, and Benguela systems, but not in California. They

projected that upwelling in these three systems will start earlier, end later, and intensify at high latitudes, reducing latitudinal variation in upwelling.

Rykaczewski *et al.*, (2015), using coupled ocean-atmosphere models, linked poleward shifts in major ocean high-pressure systems to changes in upwelling winds across all four EBUS. Their findings partially diverged from those of Sydeman *et al.*, (2014) and Wang *et al.*, (2015), who supported Bakun's hypothesis (1990). Instead, Rykaczewski *et al.*, (2015) proposed that anthropogenic changes in upwelling-favorable winds are driven by poleward shifts of high-pressure systems rather than increasing land-sea thermal gradients. García-Reyes *et al.*, (2015) suggested that upwelling systems may be more sensitive to this mechanism than to direct ocean-land temperature differences. They also found that sea level pressure (SLP) does not respond directly to air temperature (Tas), implying a more complex relationship between anthropogenic forcing and upwelling-favorable winds.

During summer, poleward boundary winds in upwelling zones are projected to intensify, while equatorward boundary winds weaken. This latitudinal dependence aligns with Sydeman *et al.* (2014) and Wang *et al.*, (2015). However, unlike these studies, which provided some support for Bakun's hypothesis on upwelling intensification, Rykaczewski *et al.*, (2015) demonstrated that projected changes in upwelling-favorable winds are not directly linked to broad increases in land-sea temperature differences.

Strong upwelling intensification signals observed in some systems align with climate change-induced warming patterns. Analyzing long-term SST trends in the Canary upwelling zone, Polonsky and Serebrennikov (2018) reported strengthened wind activity along the northwest African coast over the past 30 years, driving localized wind-driven upwelling. They identified two key wind trends shaping the spatiotemporal SST structure in the region.

Abrahams *et al.*, (2021) found inconsistent trends across EBUS. Their analysis showed that SST decreases (increases) are linked to more (fewer) upwelling events, weaker (stronger) upwelling intensity, and reduced (increased) cumulative upwelling intensity, with regional variability within EBUS. The Humboldt system was the only one displaying a consistent upwelling intensification pattern from north to south. However, they found no clear evidence linking these changes to wind dynamics, reporting no significant trends in upwelling-favorable winds along the Peruvian coast.

Trends in coastal upwelling intensity were analysed during the late 20th century in the EBUSs (Narayan *et al.*, 2010) using upwelling indices based on wind stress and HadISST. The results give additional support to Bakun hypothesis, and showed a significant increase of coastal upwelling in all regions except for Peru, after 1960. They found an ambiguous direct link between the climate mode of variability (AMO, PDO, NAO) and the future increase of upwelling intensity off Northwest Africa (NWA) and California respectively. Because of the weak and negative correlation between the NAO and PDO indices, and meridional wind stress, and lack correlation with the SST index.

Recent intensification of upwelling was described for the African coast (McGregor *et al.*, 2007), but other analysis of wind data showed differences in trends at subregional scale (Alvarez *et al.*, 2008, Pérez *et al.*, 2010, Santos *et al.*, 2011), a general weakening in the region (Pardo *et al.*, 2011) or no clear evidence of upwelling decrease (Barton *et al.*, 2013; Benazzouz *et al.*, 2015). Indeed, estimations based on regional climate models predict an increase in upwelling-favourable winds in the region (Casabella *et al.*, 2014). Satellite-derived chlorophyll series did not reveal a consistent trend through the region (Bode *et al.*, 2011, Alvarez *et al.*, 2012, Benazzouz *et al.*, 2015) but in situ determinations near the coast suggest large year to year variations (Bode *et al.*, 2011) or even increases at decadal time scales (Pérez *et al.*, 2010). These discontinuities of ocean surface cooling events over

Northwest Africa coast have been also underlined by Benazouzz *et al.*, (2014). Many studies have attempted to understand how EBUSs will respond to anthropogenic climate change, using both historical observations and IPCC climate model projections data (Sydman *et al.* 2014; Benazouzz *et al.*, 2015, Sylla *et al.*, 2019, Varela *et al.*, 2022). Model projections indicate a future weakening of tropical upwelling in the Benguela and Canary upwelling regions, located equatorward of 20°, due to reduced alongshore winds.

Relevance to Northwest African Upwelling, Bakun's hypothesis provides a framework for investigating long-term trends in wind-driven upwelling, SST biases, Ekman transport, and links between upwelling changes and climate indices (NAO, ENSO). Studies have examined this hypothesis in the Canary Upwelling System (CanUS), including the Senegalo-Mauritania upwelling (Benazouzz *et al.* 2015; Sylla *et al.*, 2019; Varela *et al.*, 2022; Vázquez *et al.*, 2022).

Cropper *et al.*, (2014) found no clear link between wind intensification and SST cooling. Their study highlighted pronounced interannual variability in the central and northern CanUS, while seasonal variability was more dominant in the central and southern regions. They observed high cross-shore Ekman transport in recent decades, peaking in 1999, 2002, 2004, 2007–2010, and a strengthening of upwelling-favorable wind stress in northern CanUS, partially supporting Bakun's hypothesis. However, their analysis (1981-2011) showed distinct warming trends, contradicting Bakun's prediction of enhanced cooling with stronger winds.

In the Senegalese-Mauritanian region, Cropper *et al.*, (2014) reported an SST increase of 1.71°C (0.57°C/decade) for SST min and 1.28°C (0.44°C/decade) for SST max, contradicting Bakun's hypothesis. While wind intensification was observed, significant cooling did not accompany it. Benazouzz *et al.*, (2014) found that while SST responds

quickly to wind changes, oceanic responses occur over longer timescales. Their later work (2015) partially supported Bakun's hypothesis, especially in northern CanUS. They found increasing upwelling-favorable wind stress but no significant SST-based upwelling index trends in central and southern CanUS.

Climate model outputs, including CMIP global and RCM regional models, have been used to assess future upwelling trends (Xiu *et al.*, 2018; Sylla *et al.*, 2019; 2022; Vázquez *et al.*, 2022; 2024, Varela *et al.*, 2022). Most of climate models often predict stronger coastal winds under global warming, but regional variability suggests inconsistent intensification across upwelling systems. While some models project future upwelling intensification, others indicate a decline. Studies (Bakun *et al.*, 2015; Rykaczewski *et al.*, 2015; Quilfen *et al.*, 2021) predict a long-term poleward shift in ocean high-pressure systems, alongside increased ocean acidification and deoxygenation in upwelling regions (Gruber *et al.*, 2011).

Along the Oman coast, Praveen *et al.*, (2016) found intensified upwelling using a Regional Ocean Model forced by CMIP5 outputs, while upwelling weakened along the Arabian coast due to weaker monsoon winds. Using CMIP5 outputs, Terada *et al.*, (2019) found a significant decline in equatorial upwelling in the eastern Pacific, linked to weakened Ekman pumping, trade winds, and enhanced stratification. In the equatorial Atlantic, where climate models tend to underestimate upwelling, reductions near the surface were closely related to local wind changes and dominated by diapycnal upwelling. In contrast, Liu *et al.*, (2023) identified an increasing trend in coastal upwelling intensity in the South China Sea based on SST data from satellite observations and reanalysis (1982–2020).

Gómez *et al.*, (2021) analyzed the Peruvian upwelling system using 31 CMIP5 models under RCP8.5, finding weak mean upwelling-favorable wind changes (≤ 0.2 m/s), with slight summer decreases (0–5%) and winter increases (0–10%). Using observational data, Walker

(2020) examined upwelling intensification and poleward migration, highlighting the role of Hadley cell dynamics. Yves *et al.*, (2021) analyzed upwelling wind trends in the California system (1996–2018), reporting a >25% seasonal upwelling increase in core regions but conflicting southern trends between satellite and model data. However, all datasets agreed on stronger equatorward winds in winter and spring.

The latest version of CMIP climate models, projected poleward shifts of upwelling-favorable winds in the high latitudes (Sylla *et al.*, 2019; 2022; Vázquez *et al.*, 2022; 2024; Varela *et al.*, 2022). With the high resolution of CMIP6 models (under SSP5-8.5), Varela *et al.*, (2022) predicted the increase of SST in both offshore (4 °C) and coastal upwelling (2.5 °C) regions caused by a weakening of upwelling in the southernmost, and the northward displacement of Canary upwelling system at the end of the 21st century. The SST difference between coast and offshore observed on the west coast of Africa was up to 3 °C.

In line with Wang *et al.* (2015), Brandt *et al.* (2024) used CMIP6 projections to predict stronger future upwelling in the southern Benguela system. Conversely, in the northern Benguela and tropical Angola upwelling regions, they found a future weakening of upwelling-favorable winds as in the southern of Canary systems (after 20°N) due to reduced alongshore winds (Bograd *et al.*, 2023).

Cropper *et al.* (2014) analyzed various upwelling indices (1981–2010) and found increasing upwelling-favorable winds north of 20°N and increasing downwelling-favorable winds south of 20°N. CMIP5 and CMIP6 models have struggled to simulate upwelling dynamics in CanUS and the Gulf of Guinea (Sylla *et al.*, 2019, Vázquez *et al.*, 2022, Varela *et al.* 2022, Chang *et al.* 2024, Ideki and Lupo 2024). Under RCP8.5, Sylla *et al.*, (2019) projected a moderate upwelling increase in northern Senegal-Mauritania and a decrease in the south due to wind shifts driven by Azores anticyclone displacement.

Despite improvements in high-resolution climate simulations, models still fail to capture local upwelling processes. Xiu *et al.*, (2018) emphasized that GCMs lack sufficient resolution for mesoscale coastal dynamics, while Abrahams *et al.*, (2021) noted challenges in proving wind-driven upwelling changes under climate change. Hahmann *et al.*, (2022) found CMIP models overestimate oceanic wind resources while underestimating land wind resources. High-resolution regional models improve mesoscale process representation (Chang *et al.*, 2023), revealing complex upwelling dynamics beyond Bakun's hypothesis. Gutierrez-Guerra *et al.*, (2024) validated this with deseasonalized SST data, attributing discrepancies to wind stress dataset differences (Narayan *et al.*, 2010) and methodological variations.

Quilfen *et al.*, (2021) highlighted that upwelling trend depend on data sources, methods, and time periods. Regional climate models better capture CanUS upwelling patterns than GCMs (Vázquez *et al.*, 2022). The ROM model accurately simulated mesoscale processes and upwelling filaments absent in GCMs, outperforming MPI-ESMs and CMIP5 models in wind stress and SST representation.

Vázquez *et al.* (2024) examined future upwelling changes using a high-resolution regional climate model under RCP8.5. Their results projected reduced interannual variability in coastal upwelling during winter, emphasizing significant latitudinal and seasonal changes in wind field due to climate change. They indicated that ocean stratification and wind variability play competitive roles, with enhanced Azores High activity intensifying downwelling and upwelling-favorable winds in Iberian upwelling regions. However, in CanUS, increased stratification and weakening winds result in shallower upwelling. Sylla *et al.*, (2022) found that higher model resolution alone does not guarantee improved upwelling simulation, as lower-resolution versions sometimes performed better. Varela *et al.*, (2022)

showed that CMIP6 models generally overestimate nearshore SST in EBUS), except in CanUS.

Otero *et al.*, (2023) linked long-term thermohaline variability in CanUS to regional meteorological factors, noting that upwelling trends remain uncertain despite global warming. Comparing regional and global climate models, Vazquez *et al.*, (2021) found regional models superior in reproducing observed seasonal and interannual variability. The regional models simulated coastal SST and upwelling indices with high accuracy, effectively transferring upwelling waters offshore. Their study reaffirmed that high-resolution models better capture mesoscale coastal dynamics. These future dynamics of upwelling will be shaped by both wind forcing and oceanic processes, requiring improved high-resolution modeling for better predictions.

Although the increase in global temperatures is unquestioned, there is ongoing uncertainty about how anthropogenic climate change will impact the mechanisms and processes driving productivity in coastal upwelling systems (Abrahams *et al.*, 2021; Gutierrez-Guerra *et al.*, 2024). To further examine the mean upwelling response to sustained anthropogenic global warming, three climate change scenarios from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) were used in this study. Despite of this studies, the predictability of the future behaviour of the EBUS is still uncertain.

Considering the limitations of the previous results, we aim to explore the capacity of two artificial intelligence models such as Long-Short-Term Memory (LSTM) and Convolutional Neural Network (CNN) machine learning models to reduce climate model uncertainties in predicting the interannual variability of coastal upwelling along the Northwest African coasts.

Historically, Artificial Neural Networks (ANNs) have been employed for the prediction of SST patterns (Tangang *et al.*, 1997; Tang *et al.*, 2000) for forecasting SST using the empirical orthogonal functions of wind stress and SST anomalies as inputs data. Further advance, works of (Wu *et al.*, 2006; Tripathi *et al.*, 2006), who developed multi-layer perceptron models for forecasting SST anomalies, demonstrating the superior predictive capabilities of ANNs over traditional methods of linear regression and canonical correlational analysis (Gupta and Malmgren, 2009; Patil and Deo, 2017). Based on the historical techniques, our study explores the application of two sophisticated machine learning (ML) and deep learning (DL) models for upwelling index predictions. Random Forest, Gradient Boosting Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) including LSTM architectures were particularly adept at processing the time-series data, marking a significant leap forward in our ability to predict offshore Ekman transport and SST-based upwelling index with accuracy (Reichstein *et al.*, 2019).

CHAPTER THREE

METHODOLOGY

3.1 Study Domains

This study is focused on the Northwest African and Gulf Guinea coastal upwelling regions which are part of the North Atlantic subtropical and tropical gyres and the eastern Atlantic boundary upwelling systems. The Northwest African coastal upwelling region includes the Senegal-Mauritania upwelling system (SMUS) which extends from the northern tip of Cape Blanc at 25° N to south of Senegal and Guinea about 10° N. The Gulf of Guinea upwelling system (GGUS) is located from Cote d'Ivoire to the east part of Nigeria coasts (10° W-5°E) (Fig. 3.1a, b, c). The topography of the study areas includes the continental shelf and slope that form the coastal band (red) and the open-ocean (orange boxes).

From the climate perspective, the region is driving by the tropical climate zone. The regional Climate conditions is dominated by the motion of the intertropical convergence zone (ITCZ) modulated by northeasterly and southwesterly trade winds which are generated by the Azores and Saint-Helen high-pressure systems. Precipitations vary gradually from the north toward the equator with average cumulative between 500 mm and 1500 mm from the Sahel to Gulf of Guinea regions, respectively. From the oceanographic perspective, the region is governed by several regional ocean currents (Fig. 3.1d) such as the Azores current (AC), Canary current (CC), Canary upwelling current (CUC) and poleward current (PC) so-called Mauritania current (MC), which formed the North Atlantic Subtropical Gyres (NASG) system; the Nord Equatorial current (NEC), North Equatorial countercurrent (NECC), Poleward Upwelling Current (PUC) and Guinea current (GC) which formed the North Atlantic Tropical Gyres (NATG) system.

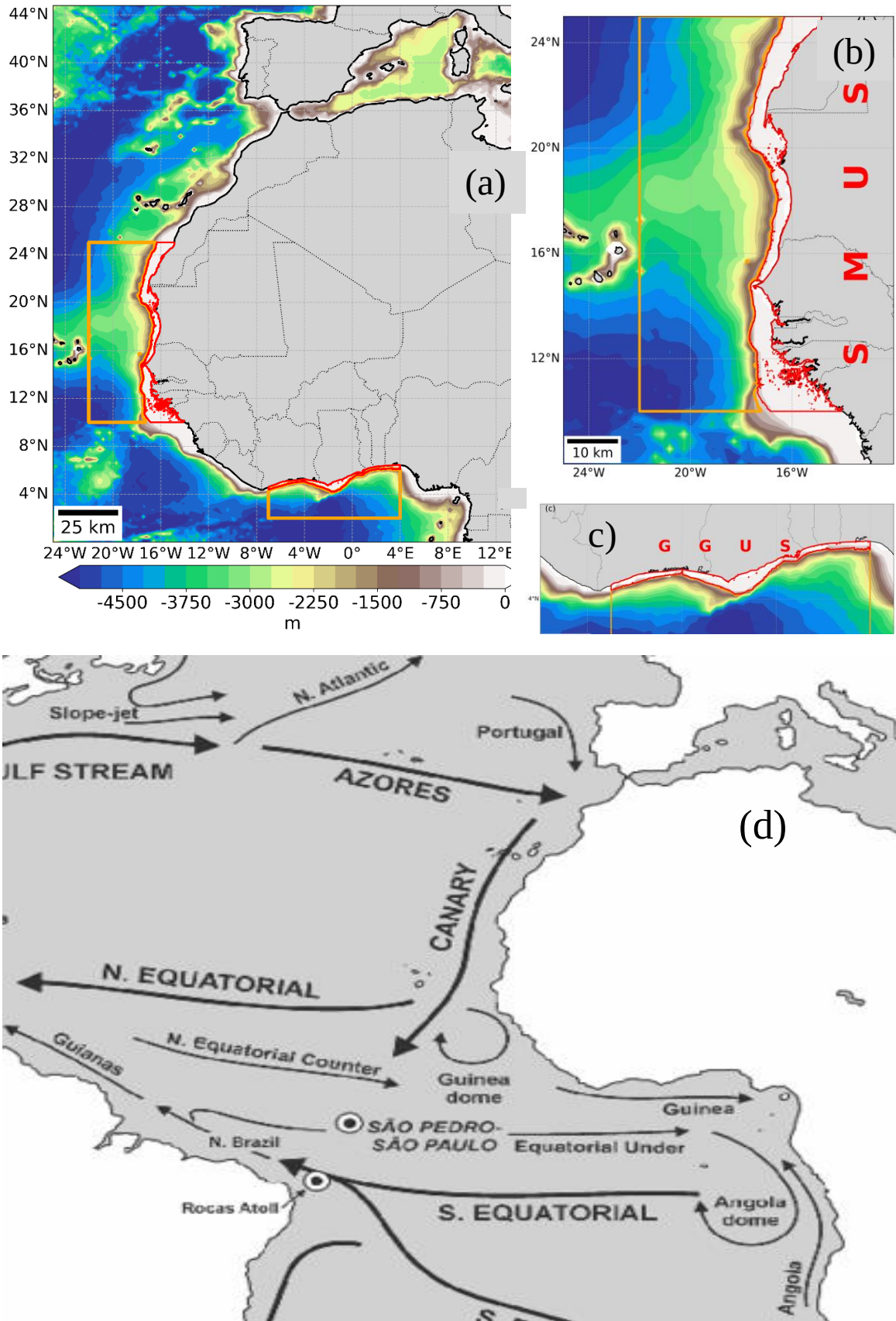


Figure 3.1: Presentation of study areas, including Senegal-Mauritania (b) and Gulf of Guinea (c) coastal topography, and regional ocean currents (d).

The two ocean current systems drive the general circulation of the North Atlantic Central, dense and saline Water masses (NACWs) and the South Atlantic Central warm and less saline Waters (SACWs) (Pelegrí and Peña-Izquierdo, 2015), respectively. The two ocean current systems are separated by the Cape Verde frontal zone (CVFZ).

The combination of these climate (atmospheric) and oceanographic conditions have significant impacts on the seasonality of Northwest African coastal upwelling systems which are the target of this study.

3.2 Data Sources

For this study multiple data including atmospheric and marine variables were collected from 1982 to 2022. These datasets include physical and biogeochemical variables, such as sea surface temperature (SST), winds and wind stress fields, ocean velocities, sea level anomaly (SLA), sea surface height (SSH), sea surface salinity (SSS), dissolved oxygen (O_2), nitrate (NO_3), chlorophyll-a concentration, and climate indices such as AMM, AMO, ATL3, ENSO, NAO, ONI, NOI, PDO, PNA, TNA, indices. These datasets are in-situ observations (station and satellite observations), reanalysis products and model outputs available on the European Centre Medium Range for Weather Forecasts (ECMWF) climate data store (CDS) site, Copernicus Marine Service platforms, the site of Climate Prediction Center (CPC) for the National Oceanography and Atmospheric Administration (NOAA), and the Deutsche Klima Research Zentrum (DKRZ), respectively.

3.2.1 In-situ Data

In situ data includes reconstituted station and satellite observations. Station observations include SST data from the Met Office Hadley Centre (HadISST), Cosmic Background Explorer (COBE), Extended Reconstructed Sea Surface Temperature (ERSST-v3b). Satellite data is the continuous observations of SST (Good et al., 2020), ocean color

(chlorophyll-a concentration) from the Moderate Resolution Imaging Spectroradiometer (MODIS) of the National Oceanic and Atmospheric Administration (NOAA), and Climate Hazards Group Infrared Precipitation with Stations (CHIRPS). OSTIA and CHIRPs products uses satellite data as well as in-situ measurements to provide global, daily, gap-filled SST and precipitation fields. Both SST, precipitations and chlorophyll-a (Chl-a) concentration are at 5 Km and 4 Km of grid, available from different time-scales (Table B1). The ocean bathymetry was taken from the General Bathymetric Chart of the Oceans bathymetry (GEBECO Bathymetry Compilation Group 2023) and remapped onto reanalysis grid (0.25°x0.25°).

These in-situ SST and ocean Chl-a were used to characterise the upwelling conditions, highlighting the dynamical and interannual variability in each upwelling system. The data was also used for the synoptic detection of marine heatwave episodes, and the climate model evaluations. The precipitation data was used to assess impacts of MHW episodes on the regional total rainfall.

3.2.2 Reanalysis Products

Oceanic Reanalysis data: the reanalysis products include the wind stress, SST, ocean velocity, sea surface height, sea surface salinity and mixed layer depth (1980-2023) obtained from the global Mercator Ocean physics reanalysis (GLORYS) (Lellouche *et al.*, 2021), and the five generation of ocean reanalysis system (ORAS5). Additional dissolved oxygen (O_2) and nitrate (NO_3) datasets were extracted from GLORYS. GLORYS data are available in daily from 1993–2021 with 1/12° and 50 vertical levels while ORAS5 are monthly data available from 1958 with 0.25° horizontal resolution and 75 vertical levels.

Atmospheric Reanalysis data: the atmospheric reanalyses are constituted of winds and SST data from ERA20C, ERA-Interim, ERA5 (Hersbach et al. 2020) available on the ECMWF

platform and the National Centre of Environmental Prediction (NCEP). Winds from NOAA20CR and Japanese 55-years Reanalysis (JRA-55) were also collected. All this data is available in monthly. In addition, ERA5 surface temperature, wind and wind stress, fields were obtained in hourly and daily. The Appendix B1 includes more detail with spatial resolutions of these datasets.

All these primary data (observations and reanalysis) were used to characterise coastal upwelling features, analyse the impacts of MHW episodes on upwelling dynamics and ecosystem productivity, and to evaluate climate model performances and uncertainty in the study domains.

3.2.3 Climate Model Outputs

The model data are used to assess the ability of climate models to capture upwelling features in both Senegal-Mauritania and Gulf of Guinea upwelling systems. The database used is achievable via DKRZ platform and include monthly surface winds and SST for models for climate model Intercomparison phase 5 (CMIP5) and phase (CMIP6) exercises. This dataset has already been used in different climate investigations including the EBUSs, such as the SMUS (Sylla *et al.* 2019, 2022, Varela *et al.* 2021, 2022, Vázquez *et al.* 2024) and in the GGUS (Ideki and Lupo 2024). The wind components were extracted from the historical simulations for 40 in CMIP5 and 47 in CMIP6 models, while SST were available for 48 and 59 models from the two generations of CMIP, respectively. Following our study period and the historical simulations of CMIP5, the model evaluations were limited from 1980 to 2005. Then, three climate change scenarios from CMIP6 were used to analyse the future trend of upwelling in the two systems at the end of 21st century. These scenarios include 35 models of SSP245, 30 models of SSP370 and 35 models of SSP585. The primary data used to evaluate these models are those used in the previous analysis to characterize upwelling

features. More details on climate model data used are presented in Tables 1-3 from Appendix B.

3.3 Materials and Methods

For the analysis tools, Python version 3.11 libraries in the Jupyter environment and climate data operators cdo-bindings were used for data manipulation (regridding, averaging, and some statistical operations) and visualizations.

3.3.1 Data Pre-processing

The current analysis covers 41-year period (1982-2022). Different spatial grid and temporal coverage were observed in reanalysis, observation and model data. Therefore, all the datasets were aligned in a common grid 0.25° for marine heat detection or T63 $\sim 1.8^\circ$ for model evaluations. The hourly and daily observations have been often resampled in daily and monthly means to match the analysis frequency, respectively. All the missing values were removed in the datasets. For bias-correction, the uncertainty in the primary data were analysed using the high-resolution product as a reference data and statistically significant tests. The systematic biases in models were accounted for, using both reanalysis and observational data. The wind stress components were derived from the winds data that wind stress products are not available, such as the daily ERA5 ten-meter surface wind and using the commonly used bulk formula given by:

$$\tau^x = \rho_a * C_d * |w|u \quad \text{and} \quad \tau^y = \rho_a * C_d * |w|v, \quad \text{where } w = \sqrt{(u^2 + v^2)} \quad (3.1)$$

Where τ^x , τ^y are the wind stress components derived in x and y directions; $\rho_a = 1025 \text{ kg/m}^3$, $C_d = 0.0013$ are the constant of water density and drag coefficient, respectively; u, v, are speed components in x and y directions; w is the wind speed.

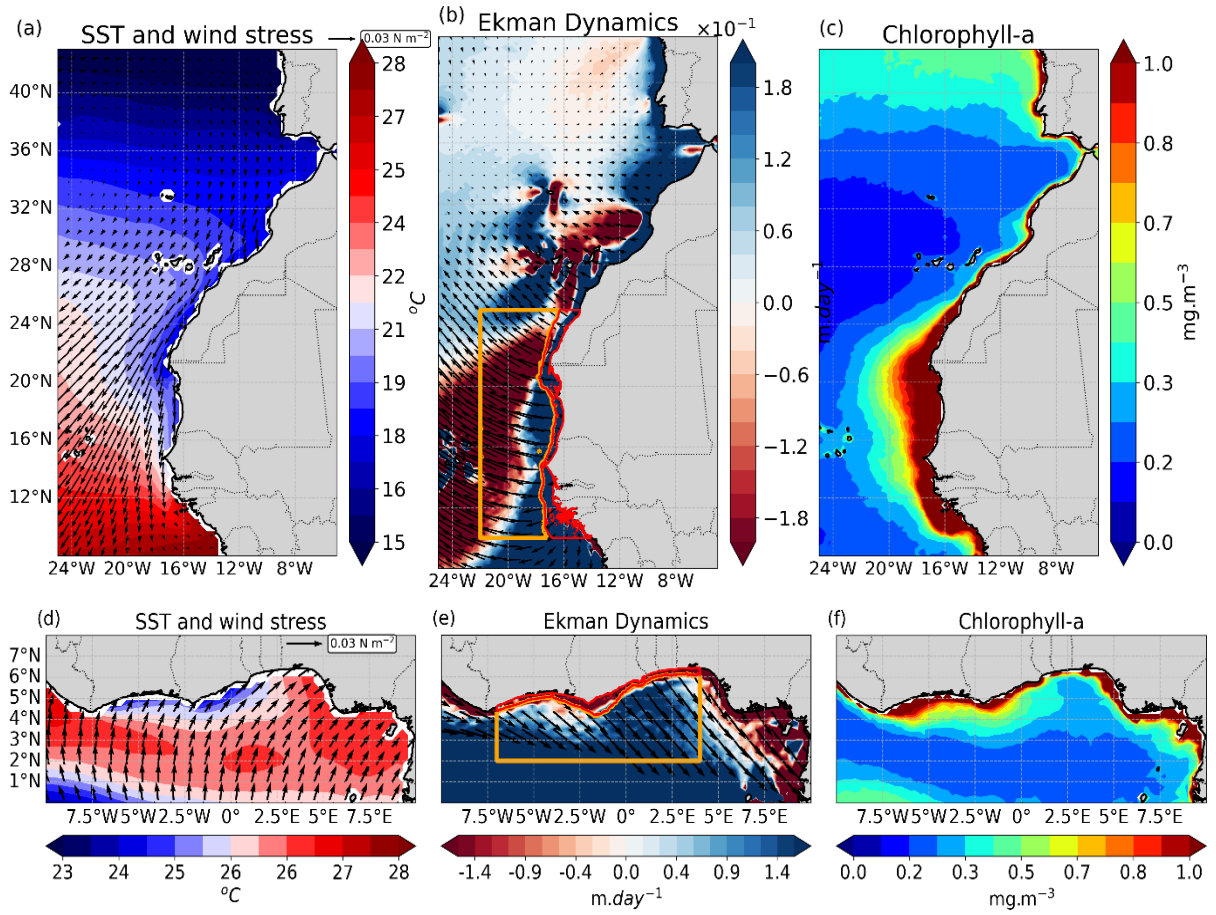


Figure 3.2 Sea surface temperature (shading) and wind stress vectors (arrows, a, d), Ekman pumping (shading) and Ekman transport (arrows, b, e), and Chlorophyll-a concentration (c, f) during the peaks of upwelling season in Senegal-Mauritania (December-May) and Gulf of Guinea (July-August) upwelling regions, respectively.

As coastal upwelling occurs on the continental shelf, the coastal and offshore boxes were defined using bathymetry from GEBECO (Fig. 3.1a, d). The coastal box was defined at 200 miles far from the coastline (by isobath 322 m), including the continental shelf and slope. This coastal box corresponds to the Exclusive Economic Zone (EEZ). The offshore box was defined at 555 m (5°) far from the coastline, where the influence of the upwelling is supposed to be insignificant (Cropper *et al.*, 2014; Sylla *et al.*, 2019; Bordbar *et al.*, 2021). The variation of the continental shelf can have impacts on the coastal upwelling dynamics and ecosystem productivity. The coastal cross-shore boxes correspond minimal local SST recorded (Fig. 3.2b, e) and the maximum chlorophyll-a concentration area (Fig. 3.2d, f). Wind stress fields and SST were extracted in the two boxes for computing UI. The SST extract in the offshore boxes were used as a “thermal reference” of what would be the coastal SST without any upwelling. The isotherm 25 °C was used as a threshold to delimit the influence zone of upwelling signal. This isotherm is selected for the eastern equatorial Atlantic upwelling because it is lower than the average SST (27°C) observed in June in this area (Bakun 1978, Picaut 1983, Caniaux *et al.* 2011). The equatorial Pacific ENSO area was defined between 170°-90°W and 5°N-5°S from the Equator. The equatorial Atlantic mode was located between 20N-0 and 3°S-3°N (Nnamchi *et al.* 2021).

3.3.2 Diagnostics and Indices of Coastal Upwelling

The analytical approach of several upwelling indices was used to characterise the dynamical and interannual variability of two distinct coastal upwelling cells along the Northwest African coasts. These upwelling indices are used in numerous previous studies (Demarcq and Faure, 2000; Caniaux *et al.*, 2011; Benazouzz *et al.*, 2014; Cropper *et al.*, 2014; Gonzalez-Nuevo *et al.*, 2014; Bordbar *et al.*, 2021) as powerful tools to analyse coastal upwelling dynamics. In this study, various upwelling indices based on wind stress, SST, SLA, ocean velocity and SSH were used to characterize the physical dynamic of coastal

upwelling. Annual cycles of surface salinity, dissolved oxygen, nitrate nutrients and chlorophyll-a concentration were used as additional indicators to characterize the biogeochemical productivity of upwelling systems.

In the tropical and subtropical eastern ocean boundaries upwelling events are primarily wind-driven (Bordbar *et al.* 2021). For the wind-driven upwelling indices, the offshore Ekman transport velocity and onshore wind stress driven which referred to Ekman pumping velocity were computed. According to Ekman's (1905) theory, coastal upwelling is induced by alongshore winds that drive offshore Ekman transport, creating a divergence near the coast. The water displaced offshore is replaced by the vertical transport from the subsurface, leading to upwelling. Along the Senegal-Mauritania coasts where trade winds are overall meridionally oriented, this upwelling is driven by the alongshore equatorward component of the wind stress, which is persistent throughout the year, and is expressed by: $M_x =$

$$\frac{\tau_y}{\rho_w \cdot f} \quad (3.2)$$

In the Gulf of Guinea where the eastward wind is favourable to coastal upwelling the cross-shore Ekman transport was expressed by: $M_y =$

$$-\frac{\tau_x}{\rho_w \cdot f} \quad (3.3)$$

Where M_x and M_y are the zonal and meridional components of Ekman transport in m^2/s ; τ_x and τ_y are the zonal and meridional components of wind stress; $\rho_w=1025kg/m^3$ is sea water density; $f = 2\Omega \cdot \sin(\varphi)$ is Coriolis parameter; $\Omega = 7.14 \cdot 10^{-5} \text{ rad. s}^{-1}$ is the angular velocity of Earth's rotation; and φ is the geographical latitude.

Ekman transport velocity (U_e) in both upwelling systems is expressed by using:

$$U_e = \frac{1}{\rho_w \cdot f} \frac{\partial \tau_y}{\partial x} \quad \text{and} \quad V_e = -\frac{1}{\rho_w \cdot f} \frac{\partial \tau_x}{\partial y} \quad (3.4)$$

Ekman transport is disturbed near the coast. Because of the existence of the coast, the offshore transport and associated divergence are compensated by vertically upwelled transport, when the alongshore current is spatially uniform. Independent of the presence of the coast, a spatial heterogeneous wind stress curl field leads to a divergence or convergence of Ekman transport that additionally forces water in the upper ocean to lift upward to the surface (upwelling) or pump downward to the deep ocean (downwelling). This type of upwelling or downwelling is based on the vertical velocity, and referred to Ekman pumping or wind stress curl driven (WSCD), leading to convergence or divergence in the Ekman transport across the ocean surface. The upwelling caused by the local wind stress curl is expressed by the vertical velocity (W_c) at the base of the Ekman layer:

$$W_c = \frac{1}{\rho_w f} \left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right) \quad (3.5)$$

Where $\frac{\partial \tau_y}{\partial x}$ and $\frac{\partial \tau_x}{\partial y}$ are the derivatives of wind stress in x and y directions, respectively. These methods allow for a comprehensive analysis of upwelling systems, crucial for understanding their ecological and climatic impacts.

The total wind-driven upwelling (W_t) was obtained by the sum of Ekman transport (W_e) and Ekman pumping (W_c) velocities:

$$W_t = W_e + W_c \quad (3.6)$$

SST anomalies near the coast is a good indicator of coastal upwelling. This coastal SST anomalies so-called SST-based upwelling index (SST_{index}) was obtained by the difference between offshore ($SST_{open-ocean}$) and inshore (SST_{coast}) boxes. Following the Ekman transport, the SST anomalies were derived zonally in the SMUS and meridionally in the GGUS as follows:

$$SST_{index} = SST_{open-ocean} - SST_{coast} \quad (3.7)$$

Both different upwelling indices based on the wind stress and SST anomalies were used to quantify upwelling intensity. The first index quantifies the physical forcing, through the Cross-shore Ekman Transport and pumping (Ekman, 1905; Bakun, 1973), the second one considers the physical response of upwelling through the SST (Benazzouz *et al.*, 2014).

The cumulative upwelling index (CUI) defined by Bograd *et al.*, (2009) was used to determine the climatological onset transition (STI) and end transition (END) dates of the upwelling. This cumulative upwelling index was calculated by integrating the daily Ekman transport along the Julian day of each year for four sections in SMUS (from 10° to 25° N) and two sections in the GGUS (from 7°W to 2°E) separated by 4° latitude. The STI was defined as the date when the minimum CUI value was reached, marking the beginning of a sustained positive upwelling index. The end of upwelling (END) was defined as the date when the CUI reached its maximum value, after which downwelling prevailed. Before integrating the upwelling index, the month with maximum downwelling was determined in each upwelling region. The integrated CUI was also used to analyse the year-by-year variability and identify individual extreme years of upwelling events. Additional upwelling metrics, such as maximum magnitude, seasonal length and the total magnitude of upwelling (TMU) were estimated the in each region. The TMU was calculated as the difference between the CUI values at the beginning and the end of the upwelling season:

$$TMU = \sum_{END}^{STI} CUI(t) \quad (3.8)$$

Ekman's theory and geostrophic balance at the synoptic scale were found as good tools to explain coastal upwelling (Tükenmez and Altiok, 2022). Thus, based on Sylla *et al.*, (2019) and Vazquez *et al.*, (2024), the cross-shore geostrophic transport velocity (T_g) due to the SSH gradient was estimated of mixed-layer depth (MLD) by:

$$T_g = \frac{g}{f} \frac{\nabla_{SSH}}{d} h \quad (3.9)$$

Where g is gravitational acceleration ($g = 9.81 \text{ m s}^{-2}$); ∇_{SSH} is the difference between alongshore and coastal onshore SSH ($SSH_{al} - SSH_{on}$). In the SMUS,

T_g was estimated by the zonally averaged geostrophic transport, while in the GGUS, it was estimated by the meridionally averaged geostrophic transport. U_{geo} is counted negative eastward following the sign convention used to quantify the upwelling. d is the distance between alongshore and coastal onshore, and h is the mixed-layer depth (in meter).

As different datasets (in-situ observations and reanalyses) were used for the same variable in each analysis, the comparative analysis was used to evaluate the ability of each dataset to represent indices.

3.3.3 Detection and Characterization of Marine Heatwaves

MHWs are defined as discrete and sustained extreme temperatures in the oceans for at least five consecutive days (e.g., Hobday *et al.* 2016). In this study, time series of SST were extracted for the coastal upwelling and the open-ocean boxes. The MHW detection algorithm was applied to these time series to identify the extreme daily warm temperature episodes. This algorithm includes the daily climatology and 90th percentile threshold calculated over the year. The time series were examined to determine whether the daily SST values meet the MHW criteria, i.e., whether or not the SST of each day exceeded the 90th percentile threshold. MHW episode was observed when the daily SST at any time exceeded the 90th percentile threshold for at least five consecutive days.

The detected MHW episodes were classified in four categories (Hobday *et al.*, 2018) based on their intensity duration and spatial extent: the moderate, strong severe and extremes events. A moderate episode is reached when the SST surplus is between the climatology

threshold and the 90th percentile threshold. The strong episode is when the exceed SST anomaly is higher than the value between the climatology and 90th threshold but not reaches the double. The severe MHW is when the SST anomaly reaches the double of the difference between climatology and 90th percentile threshold; and the extreme episode of MHW is an event that the SST anomaly is higher than the double of SST difference between climatology and the threshold. However, only the extreme events were used to analyse the potential atmospheric drivers of MHWs.

3.3.4 Analyzing Drivers and Impacts of MHW Episodes

Mixed Layer terms and anomalies of SST and wind stress were used to analyse local and large-scale drivers of MHW episodes. A heat budget is necessary to quantify the heat transport and distribution in the upper-ocean. The composite analysis of mixed layer heat budget terms was used to analyze the heat transfer during the five extremes warm (MHWs) events. Following for example Nnamchi *et al.*, (2021), the terms of mixed-layer temperature tendency ($\frac{\partial T}{\partial t}$) were derived following the equation:

$$\frac{\partial T}{\partial t} = \underbrace{u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}}_{\text{Horizontal advection}} + \underbrace{\frac{1}{h}(T - T_{-h})w}_{\text{Entrainment}} + \underbrace{\frac{Q_{net}}{\rho_w C_w h}}_{\text{Surface heat fluxes}} - \underbrace{\left(\frac{T - T_{-h}}{h}\right)w_e}_{\text{Ekman pumping}} + \epsilon \quad (3.10)$$

Where $u \frac{\partial T}{\partial x}$ and $v \frac{\partial T}{\partial y}$ are the zonal and meridional heat advection terms; u, v and w are the zonal, meridional and vertical water velocity in the mixed-layer depth, respectively; T is mixed-layer temperature; T_{-h} is the temperature at the base of mixed-layer depth; h is the mixed-layer depth; Q_{net} is the net heat flux; ρ_w and C_w are the water density and the capacity of the water; ϵ is the residual term.

Upwelling indices based on wind stress and SST, and the seasonal changes of chlorophyll-a were used to analyse the impacts of MHWs on the coastal upwelling dynamics and productivity.

3.3.5 Statistical Analysis Techniques

Statistical methods were used to analyse the spatial and temporal variability of upwelling and MHWs and their interactions. These methods were also used to evaluate the performances and uncertainties of climate models to simulate upwelling features. The statistical analysis used through this study include mean, standard deviation and statistical trend tests such Pettitt and t-tests. Composite analyses, empirical orthogonal function (EOF), principal component Analyses (PCAs), correlation and regression analyses were used as powerful statistical tools to analyse air-sea interactions during MHW events.

Composite analysis was performed for wind stress and SST anomalies and for upwelling indices to examine drivers, such as the role of large-scale climate drivers on MHW episodes, and impacts of MHW episodes in coastal upwelling areas. For this purpose, monthly SST and wind stress anomalies were computed by subtracting the long-term mean from the monthly data sets and used to analyse teleconnections between extreme upwelling events and equatorial variability modes, such as Pacific ENSO and Atlantic warming and cooling events. Composite analysis was applied to wind stress and SST anomalies for five extremes warm using SST and wind stress anomalies, Niño 3.4, Atlantic Niño and NAO indices. The composite analysis of weather patterns was used to understand different meteorological drivers of SST and wind stress anomalies.

Empirical Orthogonal Function (EOF) and and Principal Component Analyses (PCAs) are statistical methods widely used in meteorology and climate science to extract the dominant spatial and temporal patterns from large datasets. It helps to reduce dimensionality while

retaining the most significant mode of variability. In this study, EOF analysis was performed for the SST and wind stress anomalies during the MHW episodes. The principal components (PCs) were extracted from each variable. Correlation and regression analyses between these PCs and wind or SST fields were used to examine the interactions between coastal events such upwelling and MHW episodes and large-scale wind and SST variability modes. To performed this analysis, all the datasets of variables were normalised using the standardized method to ensure comparability. Missing values were handled by using the linear and neighbor interpolation techniques. The datasets were detrended removing the seasonal mean from each grid point to focused on the anomalies. For the EOF decomposition, spatial covariance matrix, eigenvalues and eigenvectors of covariance matrix, the spatial patterns (EOF) and temporal evolution were computed. The leading PCs, which explain the largest variance were used for further analysis and prediction of upwelling. The dominant EOF modes were examined to understand the relationship of upwelling patterns with large-scale climate variability.

Long-term trends in upwelling indices were analysed from 1980 to 2022 by using the linear regression models based on the gradient descent fit. For the temporal trends, the most widely used non-parametric statistical trend tests such as Mann-Kendall and Pettitt statistical trend tests and the associated Sen's slope estimate (Sen, 1968) were used to detect changes in upwelling indices in both upwelling regions.

Correlation and regression analyses performed with Pearson method were used to improve air-sea and teleconnection analyses between local upwelling and large scale-climat drivers during the major MHWs.

Wavelet coherence is a mathematical method used to analyze the signal of two timeseries. The amplitude of this coherence varies from 0 to 1, and expresses the correlation level. The

representation arrows indicate the different phases of the correlation according their direction. In the study, Wavelet analysis was used to examine the synoptical time-frequency relationship between wind stress and SST signals.

3.3.6 Climate Model Evaluations

For climate model evaluations, observations and reanalyses data were used to estimate model biases. First, the uncertainties in the primary data (observations and reanalyses) were validated by using the high-resolution products which were supposed to be more accurate. For this, OSTIA SST and ERA5 winds were used as reference products for computing biases in primary SST and winds, respectively. The model agreement and ranking were used as robust statistical tools to analyze model uncertainties. The model agreement measures the sign agreement between multi-model mean (MMM) and a single model mean biases. Model ranking include correlation coefficient and statistical metrics such as Root mean Square Error (RMSE) were used to quantify model deviations from observation and reanalysis means. Upwelling indices based on SST and wind stress were used to evaluated the performances and uncertainties of climate models (CMIP5 and CMIP6) in simulating upwelling features.

For the long-term trend analysis, both historical (1980-2014) and future projection data (2015-2099) were used. The future trends were assessed using three Shared Socioeconomic Pathways (SSP) from CMIP6: SSP245, SSP370, SSP585. Statistical trend test of Pettitt and boxplots were used to examine historical and future trends of upwelling in the context of global warming and ongoing anthropogenic climate change.

3.3.7 Future Prediction Algorithms

Despite that the drivers of upwelling are well documented over West African coasts (Polo *et al.*, 2008; Djakoure *et al.*, 2017; Illig *et al.*, 2024), the predictability of coastal upwelling

remains a topic of active scientific debate due of a lack of knowledge on all the factors that influence this event. Since the beginning of the 2020s, artificial intelligence (AI) has been used as an effective tool in scientific research, particularly in meteorology and climate science, to predict atmospheric and oceanic phenomena in real time, in both short and long term. In this section, two statistical linear regression of machine learning and two deep learning models including Random Forest regressor, Gradient Boosting regressor, Convolutional Neural Networks (CNNs), and Recurrent Neural Networks (RNNs) were such as Long Short-Term Memory (LSTM) were used to predict the interannual variability of upwelling indices such as offshore Ekman transport and SST gradient. The principal components (PCs) of local wind stress and SST anomalies, sea level anomaly, geostrophic transports, were used as model predictors. The results of the models were compared with observations and the outputs of CMIP6 models, in particular the multi-model mean of SSP585 scenario.

3.3.7.1 Model Architectures

For the prediction of upwelling indices including Ekman transport and SST gradient, both traditional machine learning algorithms and advanced deep learning architectures were employed. The selected methods include two ensemble-based machine learning algorithms such as Random Forest Regression (RFR) and Gradient Boosting Regression (GBR), two deep learning approaches of models such as LSTM and CNN, and hybrid LSTM-CNN models. This multi-model framework was designed to assess the capacity of various algorithms in capturing spatial-temporal variability in ocean-atmosphere interactions that drives coastal upwelling. These models were selected due to their ability to capture complex, non-linear relationship between multiple predictors and target variables, which are characteristic of ocean-atmosphere interactions influencing coastal upwelling.

Random Forest: Random Forest is an ensemble of learning method constructs with a large number of trees during training and outputs to reduce variance and predictive performance. In this study, the RFR model was used to estimate upwelling indices using a range of atmospheric and oceanographic predictors, such as wind stress components, sea level anomaly, SST and large-scale climate indices (e.g., ENSO, NAO, ATL3, AMM).

Gradient Boosting: Gradient Boosting is a powerful learning technique constructs with a sequence of shallow decision trees, where each new tree corrects the errors made by the previous ensemble, minimizing a specific loss function, and provides superior performance on structured datasets. In this reaserch, GBR were training on the same input variables as the RFR model, allowing the comparative assessment of their relative accuracies in capturing the temporal dynamics and variability of the upwelling indices.

LSTM: LSTM networks are a type of Recurrent Neutral Network (RNN) particularly weel-suited for modelling time series due to their ability to learn long-term dependencies and temporal patterns. In this study, LSTM was used in sequential relationship between historical climate and oceanographic variables that influence on upwelling. The input features wre normalized and structures as multivariate sequences over time windows to serve as input to the LSTM layers.

CNNs: CNNs are widely used for spatial pattern recognition. In this study, CNNs were designed and adapted to handle spatio-temporal input features such as gridded SST asnd wind fields, treating them as image-like data. Convolutional layers extracted local spatial feature relevant to upwelling dynamics, which were then passed through dense layers fro regression output. This approcach enabled the model to detect local patterns in SST and wind stress associated with coastal upwelling.

Hybrid LSTM-CNN: the Hybrid LSTM-CNN model was designed to leverage the strengths of both temporal and spatial pattern learning. The model architecture integrated convolutional layers (extracting spatial features) followed by LSTM layers (temporal dependencies). This hybrid setup allowed for an improved representation of the spatial-temporal processes underlying upwelling variability, particularly for capturing interactions between local winds, SST, and large-scale climate signals.

3.3.7.2 Training and Validation

Target and Features

For the predictive modelling approach, the monthly upwelling indices based on SST and wind stress were predicted at the interannual scale, from 2022 to the mid- 21st century. The most relevant PCs of SST and wind stress anomalies were used as input features. All the variables were normalized to ensure models learn effectively. Additional climate indices selected based on their significant correlation coefficient with upwelling indices, were included to improve predictive skill.

Model Implementations

All model fits were implemented using the Scikit-learn and TensorFlow libraries in Python. Training involves several key steps to ensure the model accurately captures the complex temporal dynamics of coastal upwelling. For the model training, the data was split into training (60%), validation (20%), and testing (20%) sets based on temporal continuity. These datasets were then structured with the input X_{train} being the sequence at previous timesteps and the target Y_{train} being the subsequent timestep. The model is trained using the Root Mean Square Error (RMSE) as the loss function (Hastie et al. 2009) monitoring both the training and validation datasets. This monitor is one of the standard statistical metrics for regression problems. It was defined by:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad 3.11$$

Where y_i is the actual values; $\hat{y}_i$ is the predict values; and n is the number of observations.

The model's performance is visualized through a convergence plot, which illustrates the decrease in RMSE over successive training epochs, indicating that the model is learning to predict SST more accurately. The hyperparameters such as the number of estimators, maximum tree depth, and learning rate (for GBR) were optimized through grid search and cross-validation. Hyperparameter tuning of the Hybrid coupled model (LSTM-CNN) was performed to optimize model accuracy.

During the training, the GBR model with a learning rate set at 0.01. This learning rate was chosen after several experimentations to ensure that the model converges efficiently without compromising the stability of the learning process.

Model evaluations

Model predictions were validated against upwelling indices derived from observations and SSP585 scenario. The model validation was performed with the Cross-Validation using time-series k-fold validation to prevent data leakage. Model performances were assessed using standard metrics including the coefficient of determination (R^2), RMSE, and Mean Absolute Error (MAE). Feature importance was also extracted to identify the most influential predictors of upwelling dynamics. Finally, model interpretability was assessed using SHapley Additive exPlanations (SHAP) tool, which provided both global and local explanations of feature contributions. SHAP values were computed for each model to identify the most influential variables driving predictions of upwelling indices such as Ekman transport and SST gradient. Visualization of SHAP summary and individual force plots allowed insights into the model's decision process, ensuring alignment with known

physical mechanisms. used to understand model decisions. The model outputs were finally analysed to assess their ability to capture seasonal and interannual variability in upwelling dynamics.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Characterization of Northwest African and Gulf of Guinea Coastal Upwelling Systems

Multiple datasets and different upwelling indices were used to characterize the dynamical and interannual variability of upwelling along the Northwest African coast.

4.1.1 Annual cycles of Coastal Upwelling Systems

This section analyses the seasonality of upwelling over the Senegal-Mauritania and Gulf of Guinea coasts highlighting key mechanisms of the eastern tropical Atlantic boundary upwelling systems.

4.1.1.1 Senegal-Mauritania Upwelling System (SMUS)

Figure 4.1 illustrates the upwelling indices based on the wind stress, SST anomalies and regional geostrophic currents in the SMUS. Fig 4.1a-c shows the seasonal variability of zonal Ekman transport (shading), wind stress curl-driven (contours) and wind stress vectors from three different reanalysis wind stress datasets. Across all the datasets (ORAS5, ERA5 and GLORYS), show a consistent pattern of intensified offshore (negative) Ekman transport between 10°N and 20°N, particularly during the boreal winter and spring (Dec-May), aligned with the peak upwelling season. GLORYS (Fig 4.1c) displays the strongest and most detailed Ekman transport and wind stress curl-driven, likely due to higher spatial resolution, while ERA5 and ORAS5 (Fig 4.1a-b) exhibit smoother and slightly weaker responses. Wind stress curl contours highlight regions of Ekman suction near the coast and around 12°–18°N, reinforcing the upwelling signature. Together, these diagnostics reveal strong seasonal and latitudinal modulation of wind-driven processes that sustain the coastal upwelling dynamics in the SMUS, with GLORYS capturing more localized features that may be critical for biophysical interactions.

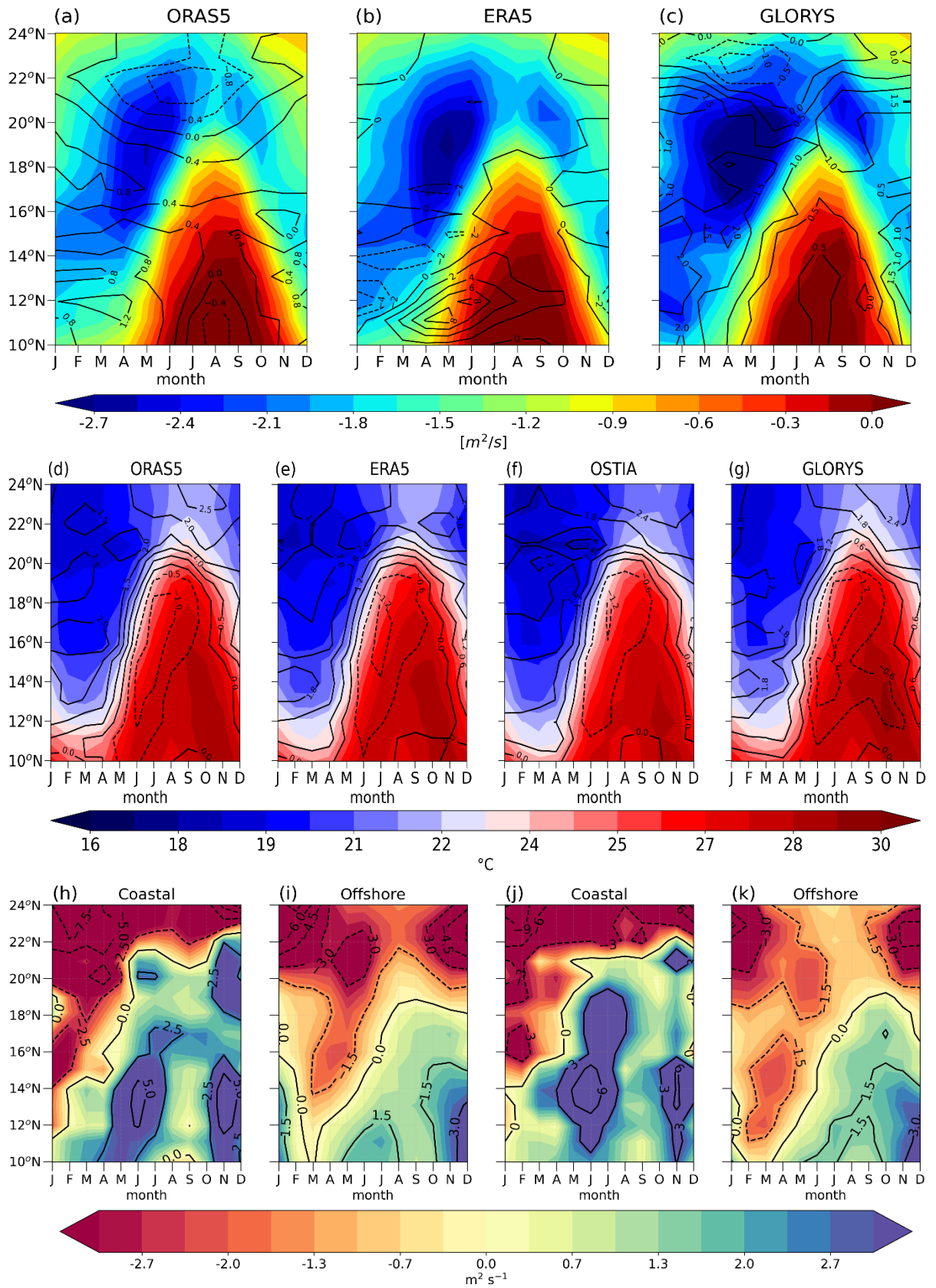


Figure 41: Annual cycles of Senegal-Mauritania coastal Upwelling System based on Ekman dynamics (a-c), sea surface temperature patterns (d-g) and onshore geostrophic transport (h-k) derived from ORAS5, ERA5, OSTIA, and GLORYS.

Figure 4.1d-g presents the annual cycle of SST (shading) and an SST-based upwelling index (UI, contours) of the SMUS, comparing four ocean products: ORAS5, ERA5, OSTIA and GLORYS. Consistent seasonal variations are also observed across all datasets, with maximum upwelling intensity (strongest positive UI values) occurring during boreal summer, particularly December-May. The upwelling tongue appears most prominent around 14–21°N, where UI reaches over 1.5 °C. Among all products, ORAS5 (d) and ERA5 (e) show stronger gradients, indicating a more intense seasonal cycle of coastal upwelling. The UI peaks slightly earlier in OSTIA (f) compared to GLORYS (g), which displays a more prolonged but less intense signal. The strongest nearshore cooling (deep blue) coincides well with the SST minimum core in all datasets. While all products capture the typical cold tongue extending northwestward from the Senegalese coast, ERA5 and GLORYS exhibit a sharper cross-shore SST gradient near 15°W, indicative of stronger or more narrowly confined upwelling. In contrast, OSTIA shows broader SST transition zones, potentially due to spatial resolution or smoother data assimilation techniques. ORAS5 appears to maintain a realistic SST gradient and coastline structure, closely resembling the canonical upwelling front patterns observed in satellite-based climatologies.

In addition to local wind-driven upwelling dynamics, the regional ocean currents play a crucial role in modulating coastal upwelling along the Northwest African coasts. The intensity and extent of upwelling exhibit significant seasonal changes influenced by shifts in wind patterns and also oceanic currents.

Figure 4.1h-k shows the monthly climatology of onshore geostrophic transport across latitude and time in the SMUS. The influence of the seasonal cycle onshore geostrophic flow on the coastal upwelling was also examined using SSH-derived geostrophic velocities from two ocean reanalyses: ORAS5 (h-i) and GLORYS (j-k). The analysis was performed separately in coastal

(h, j) and offshore (i, k) boxes to isolate nearshore divergence zones from larger-scale equatorial and sub-equatorial dynamics.

In the onshore (coastal) region, the transport is generally weaker and more diffuse in both ORA5 and GLORYS. The seasonal cycle is muted compared to the offshore box, but still hints at a basin-scale return flow or compensation from Ekman pumping offshore. Offshore geostrophic transport (negative values) dominates with values exceeding $-2.7 \text{ m}^2\cdot\text{s}^{-1}$ North of 21°N and during the boreal winter spring months (Jan–May) in the southern margin between 14°N – 20°N . This pattern is indicative of coastal divergence associated with upwelling, consistent with alongshore wind forcing during the upwelling season. Conversely, a period of an onshore transport (positive values) is observed during June–December between 14°N and 20°N and over the year in the southern margin, suggesting a relaxation phase or potential downwelling-favourable conditions. The spatial and temporal structure is broadly consistent between ORAS5 and GLORYS, though GLORYS exhibits sharper gradients and stronger extremes, particularly in the core upwelling season. This may be attributed to GLORYS's higher resolution and improved representation of mesoscale features.

This geostrophic flow may correspond to the seasonality of Poleward current describe by Klenz *et al.*, (2018) and the crucial role plays the by the North Equatorial counter-current (NECC) in the south margin of the SMUS during the boreal summer (Faye *et al.*, 2015) driving the meridional advection of warm waters associated with relatively neutral and weak upwelling-favourable winds. This underscores the importance of considering remote oceanic circulation features, such as the NECC and Guinea Dome recirculation, in addition to atmospheric forcing.

4.1.1.2 Gulf of Guinea Upwelling System (GGUS)

Figure 4.2 illustrates the seasonal cycles of the meridional Ekman transport and wind stress curl-driven Ekman pumping (a-c), across three reanalysis products (ORAS5, ERA5, and

GLORYS) over the GGUS. In all datasets, the seasonal evolution of offshore meridional Ekman transport and wind stress curl-driven shows a consistent peak during boreal summer (July-September), aligning with the primarily upwelling season in the GGUS. ORAS5 (a) exhibits a strong offshore Ekman transport (blue shading) between July and September, particularly around 1°W to 2°E , where the negative wind stress curl (dashed contours) intensifies. The June-September offshore transport is coherent with increased upwelling-favourable conditions and a dip in upwelling index observed with SST patterns. ERA5 (b) shows a broader but less intense pattern of offshore transport, with peak values slightly shifted eastward and extending later into September. The wind stress curl-driven is less focused but still supports a curl-driven upwelling mechanism near the coast. GLORYS (c) reveals a more diffuse pattern, with earlier onset of offshore transport from May onward. The transport magnitude appears weaker overall, and wind stress curl contours suggest a weak signal compared to the reanalyses, possibly reflecting model sensitivity to wind forcing.

Overall, ORAS5 captures the most coherent and intense offshore Ekman transport and wind stress curl signal in both time and space, suggesting a robust wind-driven upwelling mechanism in GGUS. ERA5 reproduces the seasonal signal well but with more spatial dispersion, while GLORYS shows more diffused patterns, possibly indicating discrepancies in wind forcing representation. These differences help contextualize the SST anomalies and thermocline structure observed in the earlier GGUS analyses and highlight the role of accurate wind forcing in simulating eastern equatorial Atlantic upwelling dynamics.

SST and upwelling index analyses across multiple datasets (ORAS5, ERA5, OSTIA, GLORYS) (d-g) show strong seasonal upwelling patterns, with a clear peak during July-September centered around 2°W to 1°E which aligns with the major upwelling season in GGUS and a weaker phase in December-February (minor upwelling season).

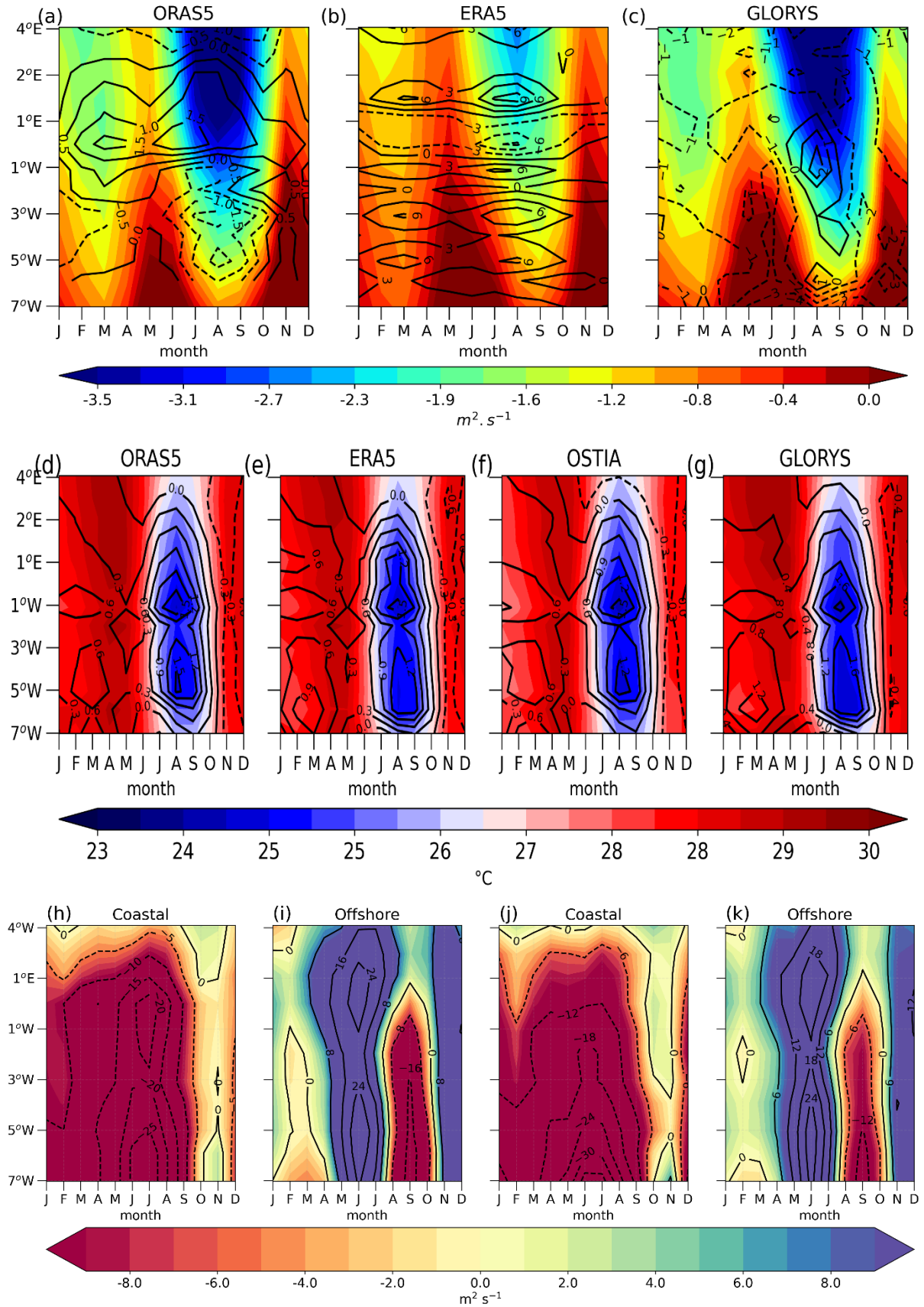


Figure 4.2: Annual cycles of Gulf of Guinea coastal Upwelling System based on Ekman dynamics (a-c), sea surface temperature patterns (d-g) and onshore geostrophic transport (h-k) derived from ORAS5, ERA5, OSTIA, and GLORYS.

All datasets reflect intense cool SSTs (below 25°C) and upwelling season (centred between 2°W-1°E), confirming the physical realism of the UI patterns. GLORYS, ORAS5 and OSTIA show the most pronounced and stratified cold tongue, aligning with the strongest and most widespread upwelling signals. ERA5 show the cooling pattern well but with a more moderate gradient and slightly lower intensity of upwelling. There's a secondary weaker upwelling event visible between December and February, especially noticeable in ERA5 and OSTIA. Despite some inter-model differences in magnitude, all datasets consistently represent the seasonal upwelling and its thermal impact on the ocean surface. OSTIA emerge as the most robust for analysing both physical upwelling intensity and SST response in the GGUS region.

The dynamical consequences of these surface patterns were examined using the onshore geostrophic transport derived from the SSH fields, to better understand the mechanisms driving this upwelling, especially the role of oceanic circulation. This component reflects the lateral (cross-shore) flow linked to the observed upwelling dynamics and evaluate how surface pressure gradient forcing translates into horizontal divergence. Figure 4.2h-k illustrates the seasonal evolution of onshore geostrophic transport in the GGUS region. The coastal box (F.g 4.2h, j) shows negative onshore transport around the year, particularly intense from January to September, with values between -10 to $-25 \text{ m}^2 \cdot \text{s}^{-1}$, especially around 7°W-2°E. These sustained onshore flows are indicative of strong coastal divergence and offshore Ekman transport, which supports persistent equatorial upwelling and aligns with climatological wind stress patterns in the region. A short-lived reversal occurs in October–November, likely marking a relaxation phase or the waning of the coastal upwelling season. Positive onshore geostrophic flow dominates east of 2°E, weakening offshore Ekman transport and upwelling intensity. Alory et al. (2021) observed this limitation of Ekman transport and upwelling conditions by positive onshore geostrophic flow and related it to the presence of the Niger River plume.

In contrast, the offshore box (Fig 4.2i, k) displays a strongly seasonal signal. A broad region of onshore transport emerges between March and July, peaking at over $8 \text{ m}^2 \cdot \text{s}^{-1}$, consistent with the influence of the equatorial undercurrent (EUC) and eastward flow associated with the Atlantic cold tongue development. This is followed by a reversal to offshore transport from August to October, suggestive of changes in wind-driven dynamics, equatorial Kelvin wave activity, or lateral shifts in the zonal current structure. Again, GLORYS depicts a more intense and localized transport signal, especially offshore, likely due to its finer spatial resolution and more detailed assimilation of altimetry data.

Both upwelling systems (SMUS, GGUS) exhibit offshore geostrophic transport near the coast during upwelling seasons, underscoring the role of coastal divergence in the sustaining vertical nutrient fluxes. However, GGUS shows stronger and more persistent offshore flow, even outside the main upwelling months, highlighting the influence of equatorial dynamics and more continuous wind forcing. The offshore regions in both upwelling systems show onshore flow during upwelling seasons, indicative of compensating return flow and broader ocean-atmosphere interactions (e.g., Ekman suction, large-scale gyre adjustment). GLORYS consistently shows stronger transports and more defined gradients than ORAS5, which may influence its suitability for studying mesoscales and submesoscale dynamics. The combined effects of alongshore wind variability, surface heat fluxes, and horizontal advection form a complex but coherent framework for understanding the interannual SST variability in this region. In summary, although the timing and location of coastal upwelling are generally agreed upon by all datasets, there are discrepancies in the magnitude and spatial sharpness of the SST and UI signals. These differences are likely attributable to their respective resolution and assimilation schemes. ORAS5 and ERA5 tend to show stronger upwelling signatures both temporally and spatially, suggesting they may be more suitable for resolving fine-scale upwelling dynamics along the NW African coast.

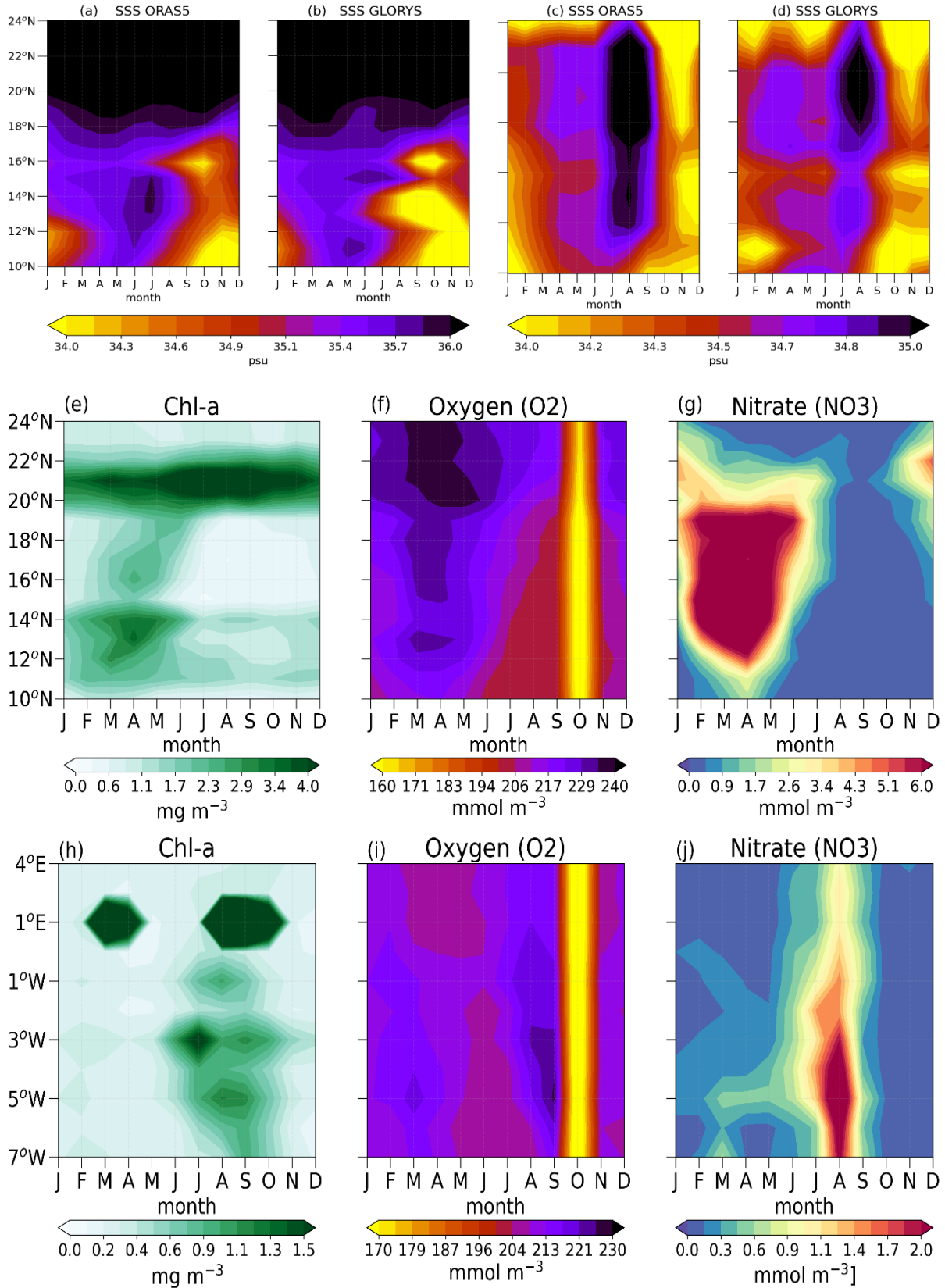


Figure 4.3: Seasonal variability of biogeochemical variables including surface salinity (a-d), chlorophyll-a concentration (e, h), dissolved oxygen (f, i) and Nitrate in the Senegal-Mauritania and Gulf upwelling systems, respectively.

Annual cycles of sea surface salinity (SSS), chlorophyll-a concentration (Chl-a), dissolved oxygen (O_2) and nitrate (NO_3) were used to illustrate the biogeochemical seasonality in the two upwelling systems (Figs. 4.3). in the SMUS, the seasonal distribution of SSS (Fig 4.3a-b) show two sub-regions, the strong concentration (>35 psu) over the year in the north of 18°N while in the southern part, the concentration of salinity is observed only during winter and spring when upwelling peaks in this region. As SMUS is partially driven by intermediate waters, this spatial variability may be linked to Atlantic Ocean gyres that drive water masses. The Chla concentration (Fig. 4.3e) is permanent around $20\text{-}22^\circ\text{N}$ and peaks during winter and spring in the seasonal upwelling region with a maximum peak observed in the southern between $12\text{-}14^\circ\text{N}$. The peaks of O_2 and NO_3 (Fig. 4.3f-g) were observed during spring season over 20°N and between $12\text{-}20^\circ\text{N}$, respectively.

In the GGUS, while the seasonality of the SSS (Fig 4.3c-d), O_2 and NO_3 peaks during the summer upwelling season (July-September), the minimum concentration of O_2 is observed during the transition period (October) as in the SMUS. The salinity peak was more representative with ORAS5 data than GLORYS products. The minimum peaks of these variables coincide with the highest SST (September-October). The connection between upwelling events and peaks of sea surface salinity (>34 psu) can be explained by considering the physical and oceanographic processes associated with upwelling. The deep ocean waters that rise to the surface are typical stable and more saline than the surface layer often diluted by precipitation and river runoff. When the upwelling occurs, it replaces this surface waters with saltier waters leading to an increase in surface salinity and nutrients. Compared to the SMUS, the concentration of the three variables is more important in SMUS than in the GGUS because of the intensity and duration of upwelling.

4.1.2 Interannual Variability of Coastal Upwelling Systems

The interannual variability analysis was based on the CUI (Fig 4.4). The integrated Ekman transport and SST gradient in both upwelling regions have allowed to identify the extremes upwelling events over the study period (1982-2022). that the interannual variability of the coastal upwelling in the two eastern Atlantic boundary upwelling systems (SMUS, GGUS) is dominated by the influence of the large-scale climate drivers such as ENSO and Atlantic Niño/Niña events. The surplus upwelling events were observed when the upwelling (Ekman transport and SST gradient) is above the climatological mean plus standard deviation, Whereas, the deficit upwelling events were identified under the climatological mean minus standard deviation. The events between the climatological mean minus the standard deviation and the climatological mean plus the standard deviation were considered as normal upwelling events.

4.1.2.1 Internnual Variability of Upwelling in the SMUS

In the SMUS (Fig. 4.4a-d), the surplus upwelling events (1983, 1989-1990, 1993-1994, 2004, 2008-2009, 2013-2014, 2017-2018) coincide with were negative ENSO phases (La Niña) with the Total Magnitude of Upwelling (TMU) higher than $500 \text{ m}^2 \text{ s}^{-1}$. In contrast, the deficit upwelling events (1982, 1984 1987, 1990-1991, 1992, 1995-1996, 1997, 2009-2010 and 2022) are consistent with the positive ENSO phases (El Niño). Almost of these extremes are consistent with Dakar Niño/Niña events described by Oettli *et al.* 2016 and Koseki *et al.* (2024), Atlantic Meridional Mode events (AMM) events highlighted by Wade *et al.* (2023) and Atlantic Niño/Niña modes (Lübbecke *et al.* 2019, Nnamchi *et al.* 2021).

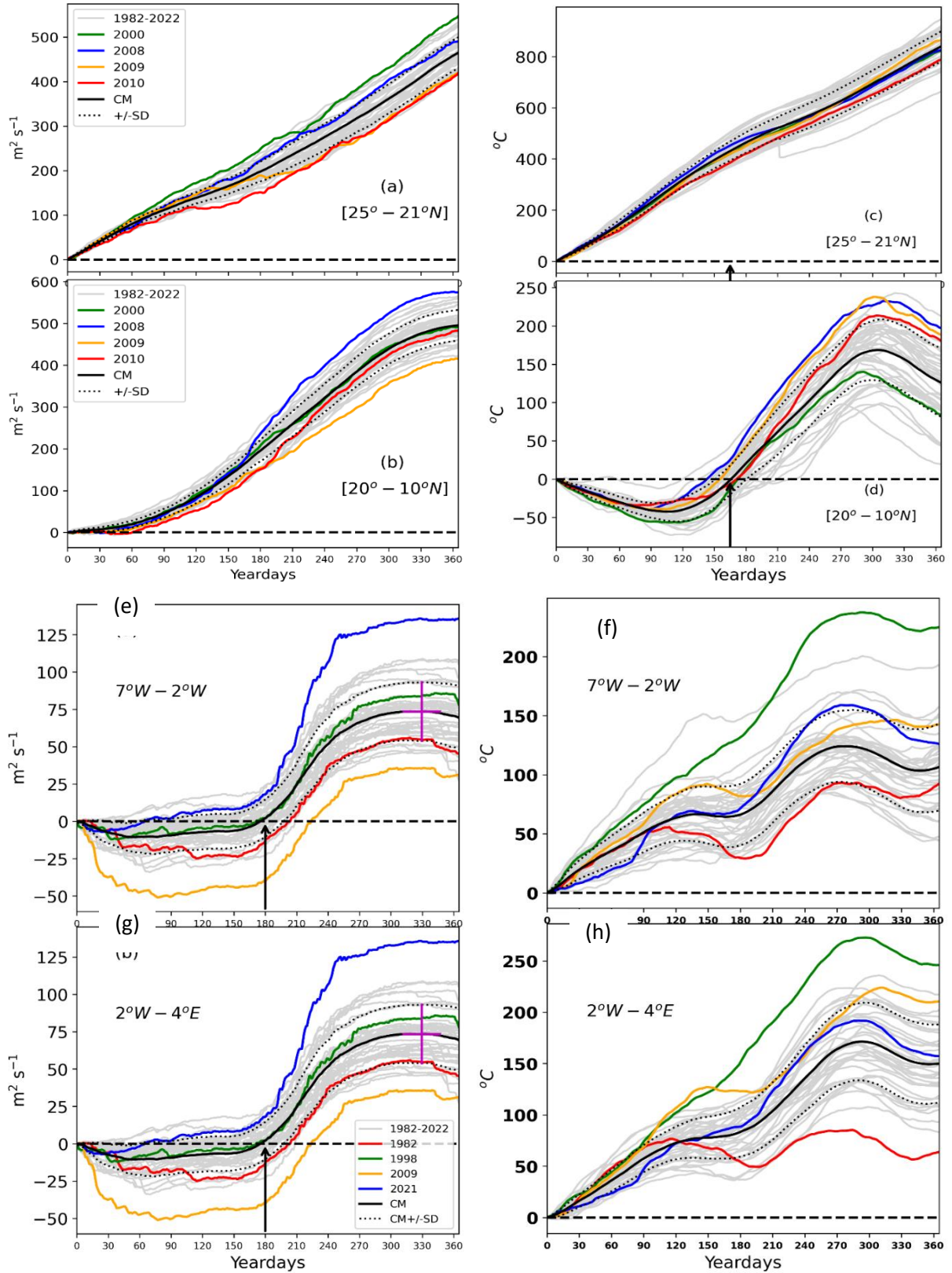


Figure 4.4: Cumulative upwelling indices (from 1982 to 2022) based on offshore Ekman transport (a-b, e, g) and SST gradient (c-d, f, h), with extreme upwelling events in the Senegal-Mauritania and Gulf of Guinea coastal upwelling sections.

The CUI also denotes that the seasonal upwelling in the SMUS starts on the 120th day (Fig. 4.4b, d, vertical arrows) when upwelling index reaches its maximum slope, and extends over 245 to 270 days. The maximum intensity of the upwelling ($\geq 2.5 \text{ m}^2 \text{ s}^{-1}$) was observed in April (152 days after the onset date, with a total magnitude of upwelling (TMU) due to zonal Ekman transport more than $600 \text{ m}^2 \text{ S}^{-1}$ (TMU of SST index $\geq 1000 \text{ }^\circ\text{C}$), while the minimum peak of upwelling coincides with the relaxation peak in August.

4.1.2.2 Interannual Variability of Upwelling in the GGUS

In the GGUS, the cumulative offshore meridional Ekman transport (Fig. 4.4e, g) and SST gradient (Fig. 4.4f, h) in the East of Cape Palmas ($7^\circ\text{-}2^\circ\text{W}$) and Cape Three Points ($1^\circ\text{W-}4^\circ\text{E}$) did not shows significant difference. The surplus upwelling observed in 1983, 1998, 2010 and 2021 ($\text{TMU} > 100 \text{ m}^2 \text{ s}^{-1}$) in the two upwelling sections coincide with the negative phases of north Atlantic cold events. Conversely, the deficit upwelling events were observed in 1992, 2009 and 2015 ($\text{TMU} < 50 \text{ m}^2 \text{ s}^{-1}$) and seem to be consistent with the warm phases of North Atlantic (Lübbecke et al. 2019).

These link between the local upwelling variability and large-scale climate modes offers the opportunity to perform in the next section the correlation analyses between climate indices and upwelling-favorable-wind stress.

The CUI in the GGUS (Fig 4.4e-f) also demonstrated that the coastal upwelling starts in the 180th day (arrows) of the Gregorian calendar (i.e., 68 days after the maximum downwelling in May) and continues for about 93 days before gradually decreasing until November. The maximum magnitude of the meridional Ekman transport ($1.5 - 1.7 \text{ m}^2 \text{ s}^{-1}$) and the SST gradient ($0.8^\circ - 1.4 \text{ }^\circ\text{C}$) was observed in August when the SST near the coast was around 23°C . The cessation of upwelling activity was observed in September, one month after the maximum peak.

4.1.3 Teleconnections Between Coastal Upwelling and Large-scale Climate Drivers

The CUI in both SMUS and GGUS shows that the interannual variability of upwelling is connected to the large-scale climate modes, particularly ENSO and Atlantic warm and cold events. This evidence was observed with the composite maps of SST and wind stress anomalies (Fig. 4.5-6) and the statistical relationships between upwelling indices and climate indices (Table A2-4).

4.1.3.1 ENSO and Upwelling Variability

The composite maps (Fig. 4.5a-d) clearly show that anomalous warming along the equatorial Pacific during ENSO phases (DJF, MAM), with accompanying atmospheric teleconnections that influence wind stress patterns over the eastern tropical Atlantic. During El Niño (Fig. 4.5a, c), both the SMUS and GGUS regions exhibit reduced wind stress intensity and positive SST anomalies, especially during boreal winter (DJF), suggesting weakened upwelling conditions. The El Niño events enhance northwesterly and northward winds and suppress upwelling along Senegal and Mauritania coasts. Conversely, La Niña phases (Fig. 4.5b, d) display negative SST anomalies and strengthened upwelling-favourable winds. These dynamical responses are supported by the correlation analysis (Tables B4), where Niño3.4 and ONI indices are significantly negatively correlated with upwelling winds (Fig. 4.5) and upwelling indices (both SST-UI and Ekman transport), especially in DJF over the GGUS (e.g., $r = -0.54$ for SST-UI and Niño3.4; $r = -0.47$ for Ekman and Niño3.4). The correlations are weaker but still present for the SMUS, particularly during DJF. These findings align with Wade et al. (2023), who showed that ENSO-induced atmospheric teleconnections modulate upwelling in the Gulf of Guinea and influence trade wind intensity in the SMUS during the boreal winter.

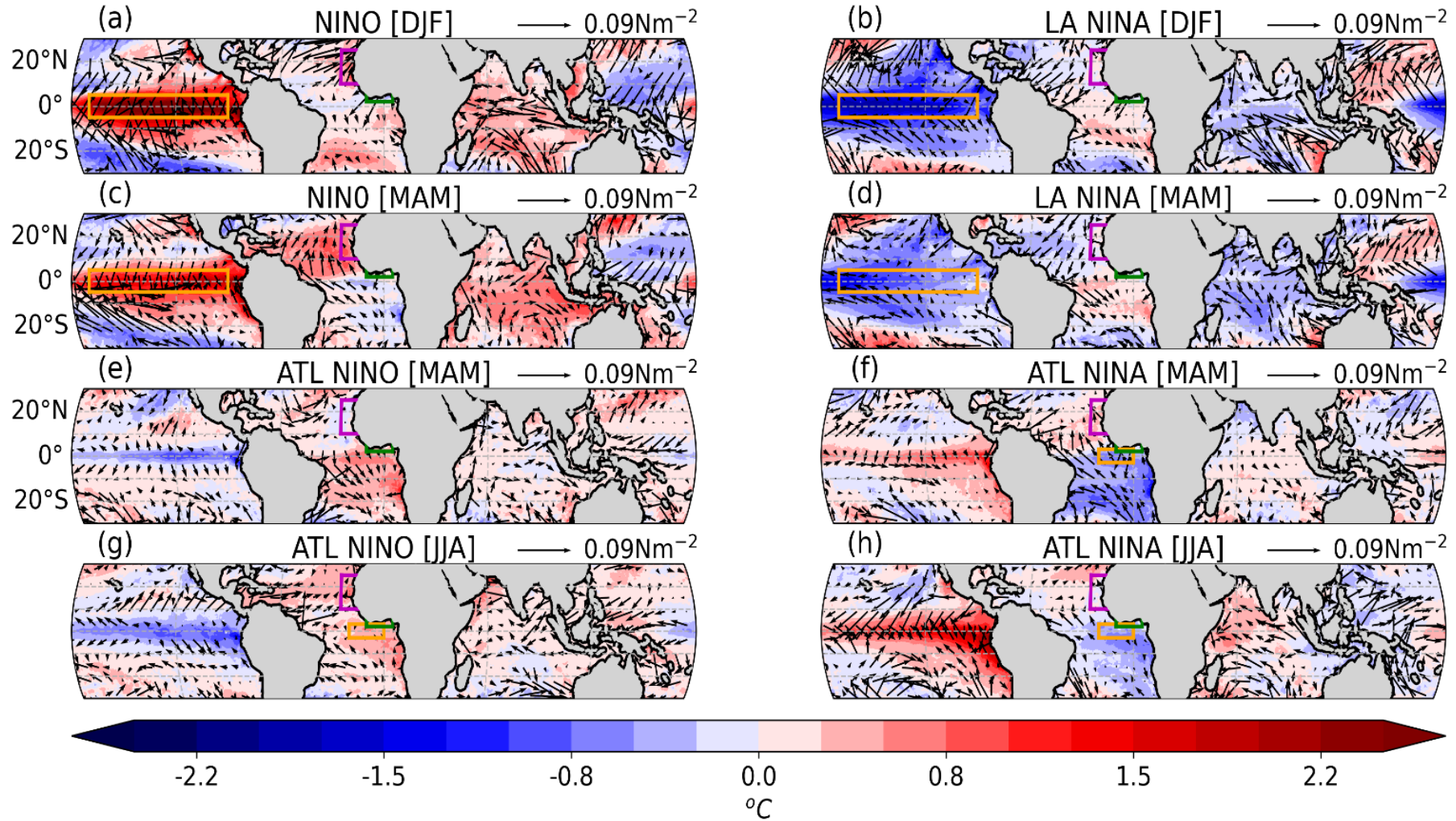


Figure. 4.5: Composite of SST (shading, $^{\circ}\text{C}$) and wind stress (vectors, N.m^{-2}) anomalies during the extreme ENSO (a-d) Atlantic mode (e-f) events observed in DJF, MAM and JJA seasons in the Senegal-Mauritania and Gulf of Guinea coastal Upwelling System (boxes).

4.1.3.2 Atlantic Niño (ATL3) and Seasonal Coupling

The impact of Atlantic Niño is particularly pronounced in June-August (JJA) (Fig. 4.5e–f), a season when SST anomalies are centred in the eastern equatorial Atlantic. During Atlantic Niño events, the GGUS shows substantial warming and weakened wind stress in particular during MAM, while Atlantic Niña years exhibit strong cooling and enhanced upwelling-favourable winds. These patterns are consistent with significant correlations observed in JJA between the ATL3 index and both upwelling indices in the GGUS ($r = -0.61$ for SST-UI, $r = -0.49$ for Ekman transport).

In contrast, the SMUS appears less sensitive to ATL3 variations in JJA, reflecting its decoupling from equatorial dynamics during boreal summer. This spatial distinction supports findings by Bordbar et al. (2021), who emphasized the regional specificity of upwelling responses to Atlantic Niño, with a stronger impact in the Gulf of Guinea compared to the Canary Current system. These patterns resemble the warm and cold Dakar Niño/Niña conditions described by Oettli et al., (2016) which are linked to weakened (Niña) and strengthened (Niña) trade winds and enhanced coastal upwelling. This supports the idea that La Niña phases can precondition or trigger Dakar Niña events through enhanced trade winds and coastal upwelling along the Northwest African margin. During ATL3 Niño summers (Fig. 4.6e), the development of warm SSTs in the eastern equatorial Atlantic appears to be accompanied by warm anomalies and anomalous onshore winds along the Senegalese coast (Pink box), reminiscent of Dakar Niño dynamics. This suggests a potential role for ATL3 Niño in enhancing the coastal warming and reducing upwelling intensity as described in Oettli et al., (2016).

Composite correlations (Fig. 4.6) between the Niño 3.4 index, ATL Niño and upwelling-favourable wind stress anomalies provided more detail on the relationship between equatorial Pacific, Atlantic variability and the Northwest African coastal upwelling systems.

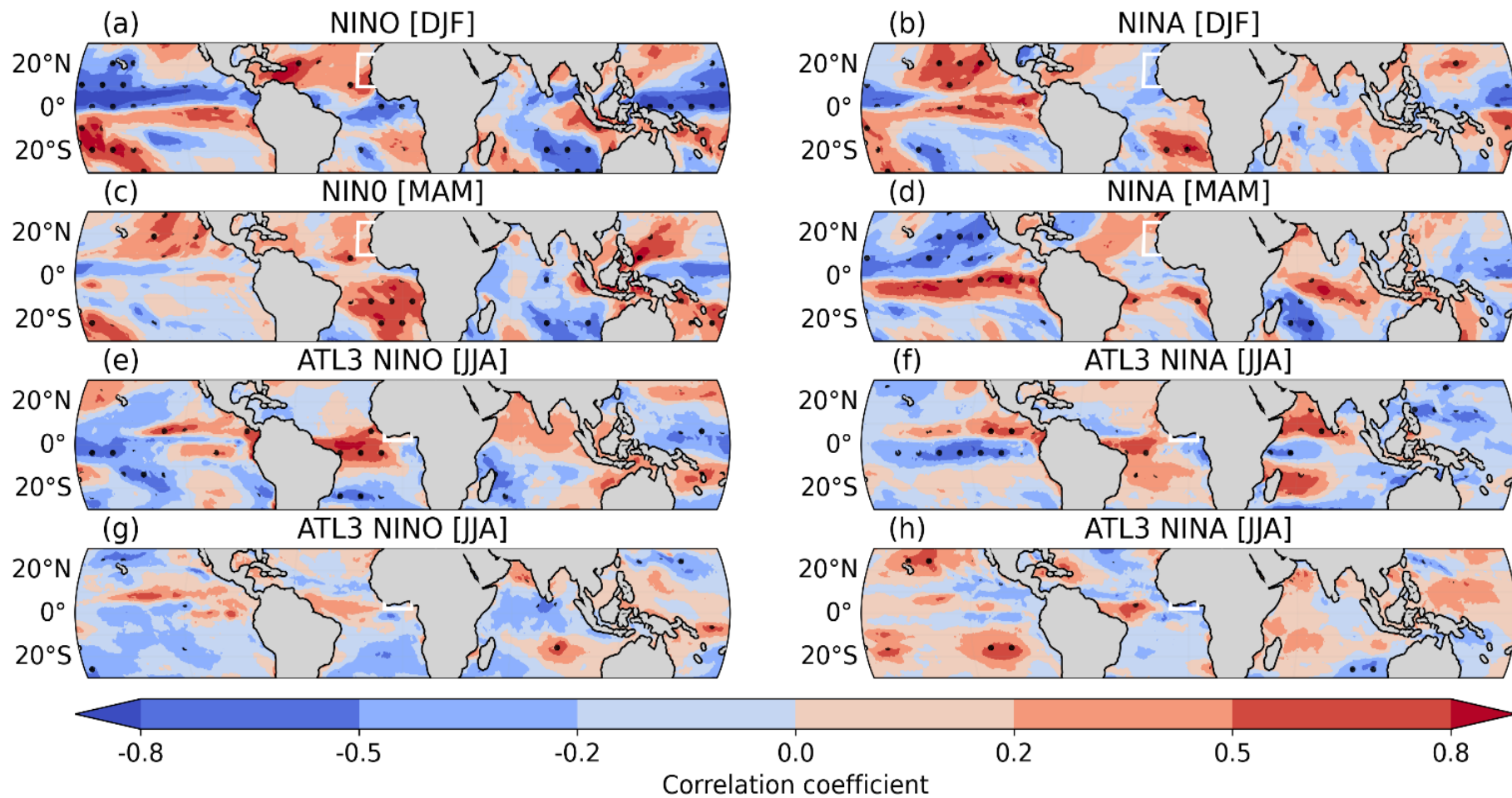


Figure 4.6: Correlation maps between upwelling favourable wind stress anomalies and the indices of extreme ENSO and ATL3 events with 95% confidence level, observed during DJF, MAM and JJA in the Northwest African and Gulf of Guinea coastal upwelling regions.

During El Niño (Fig 4.6a, c), significant positive correlations ($r \geq 0.5$) are observed in the tropical Atlantic, especially off the coast of Senegal-Mauritania, indicating enhanced southerly wind anomalies during boreal winter (DJF) and spring (MAM). These wind anomalies are consistent with a weakening of the northerly component of the trade winds (upwelling favourable winds in SMUS), which can suppress coastal upwelling and lead to warming SST anomalies in SMUS. Conversely, during La Niña events (Fig 4.6b, d), negative correlations dominate the same regions, reflecting stronger-than-normal northerly winds that can intensify upwelling along the Senegal-Mauritania coast. These wind anomalies suggest a dynamic link between Pacific ENSO events and Atlantic meridional wind variability, which may modulate oceanic processes such as coastal upwelling off Senegal-Mauritania and the Gulf of Guinea.

Figure 4.6e–h shows the correlation between ATL3 SST anomalies during MAM, JJA and zonal wind stress. Positive ATL3 anomalies (Fig 4.6e, g) are significantly associated with westerly wind anomalies across the equatorial Atlantic and into the western basin. These wind anomalies support the generation of downwelling Kelvin waves and suppressed upwelling, facilitating the development of warm SST events characteristic of the Atlantic Niño, along the Northwest African coast, especially in the Gulf Guinea coast and the southern margin of SMUS.

The historical trends of upwelling were estimated in each upwelling section using the Mann Kendall statistical test and the linear regression model fit of SST and upwelling-favourable wind stress such as meridional (in the SMUS) and zonal (GGUS) trade wind stress anomalies during the winter-spring and summer in both upwelling regions, respectively. In the SMUS, the result shows a decrease of upwelling wind stress (slope=-0.05) and increase of SST (+0.24) anomalies associated with the weakening of upwelling conditions in the permanent upwelling area. In the seasonal upwelling region, the result indicates an increase of upwelling wind stress

(slope=+0.09) and SST (slope=0.15) anomalies. This increase was more slightly pronounced in the satellite observations than in the other data sets used.

The historical trends in the GGUS shows a decreasing trend of upwelling-favourable wind more pronounced in the East (slope=-0.26) than in the West (slope=-0.08) associated with an increasing trends of SST anomalies (+0.45) and a weakening of upwelling favourable conditions. This decreasing trend can be linked to the impacts of global warming and anthropogenic climate change (Bograd *et al.*, 2023).

Overall, ENSO appears to modulate meridional wind variability primarily during boreal winter and spring, while the Atlantic Niño modulates zonal wind anomalies during JJA. These wind responses to large-climate drivers are crucial in shaping the seasonal dynamics of upwelling and SST in the eastern Atlantic, setting the stage for further impacts on geostrophic transport and regional climate variability.

4.1.4 Partial Summary

This section has examined the dynamical and interannual variability of two major eastern Atlantic coastal upwelling systems, the Senegal-Mauritania Upwelling System (SMUS) and the Gulf of Guinea Upwelling System (GGUS) using multi-source datasets from 1982 to 2022. Several upwelling indices based on wind stress, SST and ocean currents were used to assess variability and trends, with particular emphasis on links to large-scale climate drivers such as ENSO and Atlantic Niño events.

The analysis highlights how both atmospheric and oceanographic, local and remote forcings influence on upwelling intensity and timing, confirming the complex air-sea interactions that drive coastal upwelling along Northwest Africa, as reported in previous studies (e.g., Wooster *et al.*, 1976; Djakuré *et al.*, 2014; Brandt *et al.*, 2023).

In the SMUS, upwelling is mainly driven by equatorward trade winds and zonal Ekman transport during the boreal winter-spring. However, this process is modulated by regional climate variability (Capet *et al.*, 2017), ocean currents (e.g., Benazzouz *et al.*, 2014; Klenz *et al.*, 2018; Kounta *et al.*, 2018) and remotely forced equatorward wave dynamics (e.g., Polo *et al.*, 2008; Wade *et al.*, 2023). Consistent annual cycles in upwelling indices are observed across datasets, delineating a permanent upwelling zone (21°-25°N) and a seasonal zone (10°-21°N), consistent with previous classifications (Wooster *et al.*, 1976; Lathuilière *et al.*, 2008).

In the north, strong correlations between zonal Ekman transport and SST gradients confirm the dominant role of Ekman dynamics, whereas in the seasonal zone, a one-month lag between these variables suggests a delayed oceanic response, likely due to mixed-layer adjustments (Benazzouz *et al.*, 2015; Capet *et al.*, 2004). Upwelling in the SMUS peaks during March-May, while the summer months coincide with relaxation phases characterised by weakened offshore Ekman transport and reduced wind stress curl. Notably, a weakening of WSCD during the boreal summer contrasts with findings in the Angola-Benguela system (Bordbar *et al.*, 2021).

In the southern SMUS, where winds are more seasonal, WSCD and Ekman transport appear to be statistically anti-correlated. In the GGUS, the minor (December-February) and major (June-September) upwelling seasons are well documented and consistently captured across datasets (e.g., Addison 2010; Sohou *et al.*, 2020), with the major season associated with enhanced wind stress curl and Ekman suction. OSTIA, GLORYS and ORAS5 products show better agreement in this region than ERA5, indicating their relative robustness to the GGUS representation.

The role of geostrophic transport was also investigated. In both systems, negative (offshore) onshore geostrophic transport dominates during upwelling seasons, while positive (onshore) transport characterises relaxation periods. These geostrophic patterns are consistent with the seasonal behaviour of the Mauritania Current (Benazzouz *et al.*, 2014; Klenz *et al.*, 2018;

Kounta *et al.*, 2018), and the NECC (Brandt *et al.*, 2011; Faye *et al.*, 2015) in the SMUS, and the Guinea current in the GGUS (Ingham 1970; Colin 1988; Bah 1980; Djakuré *et al.*, 2017). In particular, the Mauritania Current exhibits seasonal transitions subsurface poleward during upwelling and surface intensified poleward during relaxation that affect SST and nutrient dynamics in the SMUS (Capet *et al.*, 2017).

Meridional advection by the NECC contributes to SST warming during the boreal summer by transporting warm equatorial waters towards the SMUS, offsetting upwelling driven cooling (Faye *et al.*, 2015; Brandt *et al.*, 2023). This mechanism is evident in our composites, which show warm SST anomalies during weak upwelling-favourable winds. Such interactions highlight the importance of accounting for remote oceanic circulations, such as the Guinea Dome and the NECC, alongside local wind forcing to fully explain SST variability. Furthermore, Verstraete, (1992) found that the convergence of the Equatorial Undercurrent (EUC) and the NECC enhances Gulf of Guinea coastal upwelling current.

The GGUS is dominated by the negative onshore geostrophic current peaks during boreal summer. The detachment of the Guinea (dominant onshore geostrophic current) exhibits an intensification during the boreal summer (June-September) (Ingham, 1970; Colin, 1988; Djakuré *et al.*, 2017) due to the energy tranfert by the eastward propagation of the equatorial Kelvin waves and the poleward intensification of coastal trapped waves generated by the sea level pressure gradient (Clarke 1983; Picaut 1983; Polo *et al.*, 2008; Djakuré *et al.*, 2014).

In addition, mesoscale eddies generated by these current systems (Jouanno *et al.*, 2013; Djakuré *et al.*, 2014) enhance vertical mixing, shoaling the thermocline and promoting nutrient-rich upwelling (Ndoye *et al.*, 2017; Djakuré *et al.*, 2017). High-resolution modeling and confirm that mesoscale eddies modulate both SST and chlorophyll-a concentrations, reinforcing their biogeochemical significance (Kounta *et al.*, 2018; Da-Allada *et al.*, 2017). In the GGUS, strong

negative onshore geostrophic transport during the boreal summer corresponds to the peak upwelling in the northern Gulf of Guinea. This suggests that geostrophic forcing, in addition to mesoscale variability, plays a key role in modulating the dynamics of the GGUS, consistent with previous findings.

The interannual variability analysis shows that the coastal upwelling systems along the Northwest African margin is intricately modulated by large-scale tropical ocean–atmosphere interactions, notably ENSO, Atlantic Niño/Niña, and more regionally, Dakar Niño/Niña events. These climate modes modulate the surface wind stress field, sea surface temperature (SST), thermocline depth, and atmospheric pressure gradients, all of which contribute to the strength and spatial variability of coastal upwelling.

ENSO, particularly through the Niño 3.4 index, has shown a significant lagged impact on the SST and wind stress anomalies in the SMIS. El Niño phases are known to weaken the equatorward trade winds over the Atlantic during boreal winter and spring (DJF-MAM), leading to suppressed upwelling along the Sengal-Mauritania coast due to both weakened Ekman transport and thermocline deepening (Chang *et al.*, 2006; Rodríguez-Fonseca *et al.*, 2009). The weakening of the Atlantic trade winds during El Niño events also affects the northward propagation of upwelling Kelvin waves along the equatorial Atlantic, reducing the coastal upwelling signal in the SMUS (Richter *et al.*, 2010; Lübbecke *et al.*, 2010). In contrast, La Niña phases shows the enhancement of upwelling due to the strengthening of equatorward trade wind stress and Ekman transport. Furthermore, ENSO teleconnections often have a delayed effect on the coastal wind field, thus modulating summer upwelling intensity with a lag (Bachèlery *et al.*, 2016) as observed in the northern of SMUS.

During Atlantic Niño phases (JJA), the analysis shows that warm anomalies in the equatorial Atlantic weaken the meridional SST gradient, which in turn suppresses the northwesterly trade

winds (Okumura and Xie, 2006). This weakens coastal upwelling and promotes warmer conditions along the Northwest African coast, particularly during June-September, overlapping with the season of peak upwelling intensity in the GGUS. This leads to positive SST anomalies in the SMUS region. Conversely, Atlantic Niña events strengthen the equatorial trade winds and increase coastal divergence, favoring enhanced upwelling along both the equator and the adjacent coastal margins of West Africa (Lübbecke and McPhaden, 2012; Richter *et al.*, 2013). The Atlantic Niño/Niña phases can reinforce or oppose ENSO-driven teleconnections, leading to constructive or destructive interference in the modulation of upwelling systems (Wang *et al.*, 2015).

During Dakar Niño events, our results show that the anomalous westerly and relaxed trade winds reduce upwelling and deepen the thermocline near Dakar, leading to positive SST anomalies. These conditions are often associated with reduced Ekman transport and warm SST advection from the equator. The weakening of upwelling-favourable winds observed during the summer periods support the notion that the seasonal upwelling patterns along the Senegal-Mauritania coast can be modulated by both equatorial Atlantic variability and Pacific influences, consistent with the teleconnection pathways proposed by Lopez-Parages *et al.*, (2020) and Koseki *et al.*, (2024).

In contrast, Dakar Niña events enhance the wind-driven divergence and shoal the thermocline, intensifying the upwelling signal and promoting cold anomalies (Oettli *et al.*, 2016; Lazar *et al.*, 2017; Koseki *et al.*, 2024). These patterns are consistent with Dakar Niño/Niña conditions characterized by suppressed (enhanced) upwelling and cooling of mixed-layer, as documented by Oettli *et al.*, (2016) and further elaborated by Koseki *et al.*, (2024).

Interestingly, these coastal upwelling can be both forced remotely (e.g., via ENSO or Atlantic Niño teleconnections) and generated locally via air-sea interactions, implying a dual origin

(Okumura and Xie, 2006; Capet *et al.*, 2017). Hence, Dakar Niño/Niña events can act as both a driver and a consequence of anomalous upwelling activity. The implications for regional fisheries, marine ecosystems, and climate predictability are significant, given that these upwelling anomalies can strongly impacts nutrients availability and SST-driven feedbacks. Taken together, our observational-based composites and the coupled modeling results of Koseki *et al.*, (2024) highlight the importance of both local wind–SST feedbacks and large-scale teleconnections in shaping the interannual variability of Northwest African coastal upwelling. Understanding these drivers is essential for improving forecasts of marine conditions and assessing the potential impacts of global warming on this sensitive and economically important region.

4.2 Impacts of Marine Heatwaves on Northwest African and Gulf of Guinea Coastal Upwelling Dynamics and Productivity

The abnormal increase of SST was observed as MHW episodes. The drivers and impacts of these abnormal temperature events were examined through upwelling dynamics and ecosystem productivity in the SMUS and GGUS regions.

4.2.1 Observed Marine Heatwave Episodes

4.2.1.1 MHW Episodes in the SMUS

Examining more closely at the marine heatwaves (MHWs) in the daily SST in the SMUS (using the MHW algorithm described in Section 2.3), 77 and 67 warm events were detected between 1982 and 2022 in the coastal and open ocean, respectively, at the same latitude. The major MHW events (strongest and longest) were observed in 1998, 2005, 2010 and 2020, with maximum SST anomalies above 3.5 °C and above 2.5 °C in the coastal and open ocean regions. The most intense (+5.5 °C) episode was detected in 2020 in the coastal region (Fig. 4.7a-b), while the longest (125 days) and largest (in spatial extent) episode was observed from

December 2009 to June 2010 over both the coastal and open ocean regions (Fig. 4.7c-d), with the maximum intensity around +2.55°C (Table 4.1). Other major MHW episodes were observed during the summer period in 2018 and 2022. The detected MHW episodes were classified into four categories according to their duration, intensity and spatial extent (see Methods). Most of the detected MHW episodes were moderate and relatively strong (93.5%), with maximum intensities below 2.5°C. The four largest (strongest and longest) MHW episodes (1998, 2005, 2010, 2020) and extreme. The longest episodes (1998, 2010) observed in the open ocean were strong in duration, spatial extent and cumulative intensity ($> 200^{\circ}\text{C}$), but weak in maximum intensity (2.5°C). The strongest episodes (2005, 2020) observed in the coastal region were extreme in terms of maximum intensity ($> 3.5^{\circ}\text{C}$) but relatively weak in terms of duration (< 50 days on average). More details on the characteristics of MHW in this sub-region are given in Table 4.1. The results of Fig 4.8 show that the strongest (red) and longest (orange) MHW episodes are common in maximum and mean intensities (Fig 4.8 b, d, f, h) but different in duration and cumulative intensities (Fig 4.8a, c, e, g) in both coastal and open-ocean regions. In the open ocean, the strongest episode coincides with the longest episode (Fig 4.8e-h). The linear regression analysis of MHW properties in relation to the evolution of the number of events over time shows increasing trends in duration ($s=0.16$) and cumulative intensities ($s = 0.09$) and decreasing trends in maximum and mean intensities ($s = -0.07$ and -0.13). The decrease trends may be due to the large number of moderate events (90%).

Table 4.1: MHW episodes over the coastal and open-ocean boxes in the SMUS.

Region	N_events	Imax	Imean	Icum	Duration	Start date	End date
21-25°N	89	6.25°C	4.97°C	179.48°C	25 days	07 Sep 2020	01 Oct 2020
18-21°N	79	5.31°C	3.54°C	169.42°C	18 days	06 Mar 2020	23 Mar 2020
14-18°N	93	5.57°C	3.67°C	209.52°C	47 days	22 Apr 2005	17 Jun 2005
10-14°N	84	5.59°C	3.99°C	268.0C	64 days	15 Jan 2020	22 Mar 2020

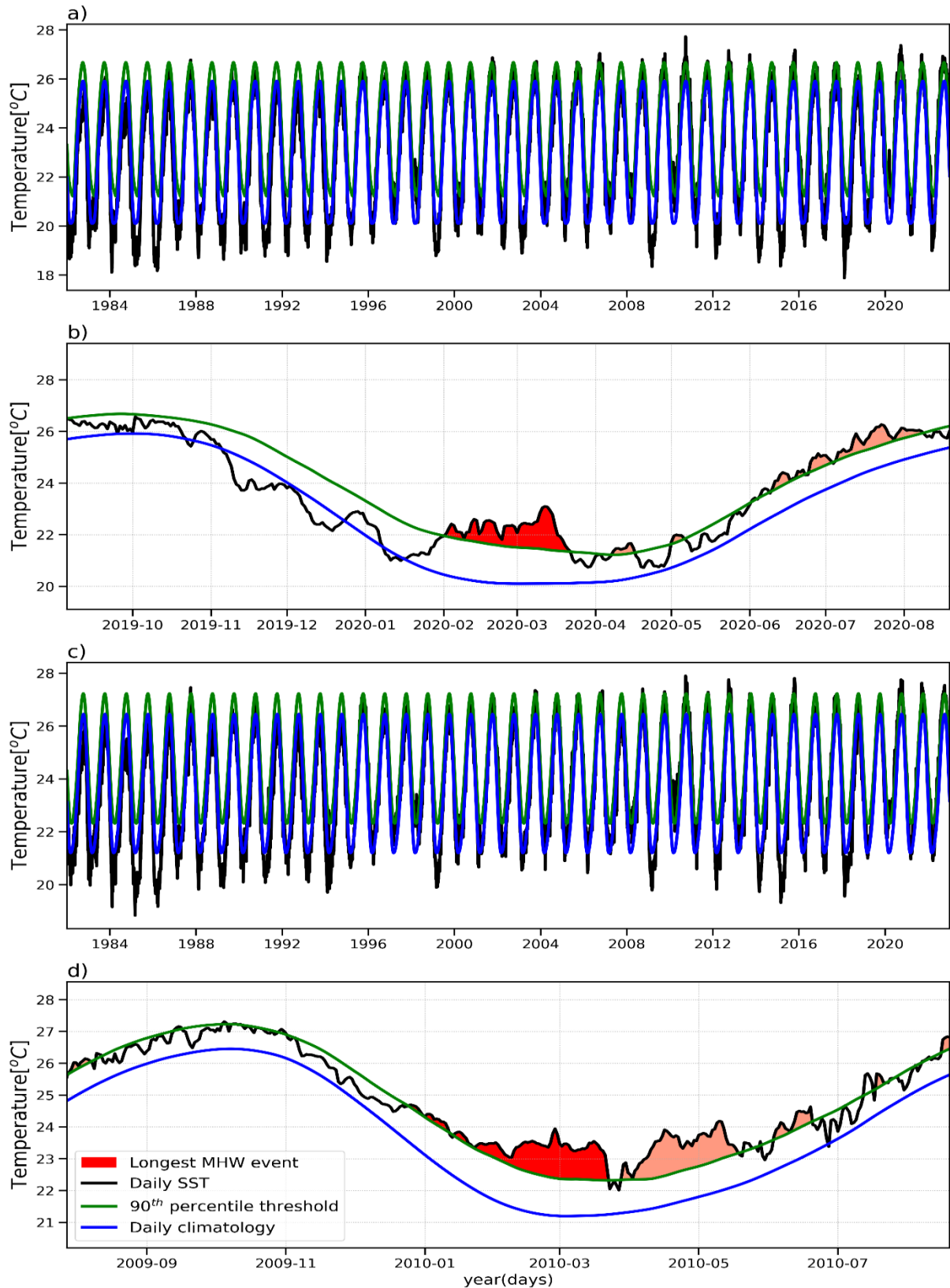


Figure 4.7: a-b SST time series and strongest MHW episode in the Senegal-Mauritania Upwelling System (SMUS). c-d SST time series and longest Marine Heatwave (MHW) episode.

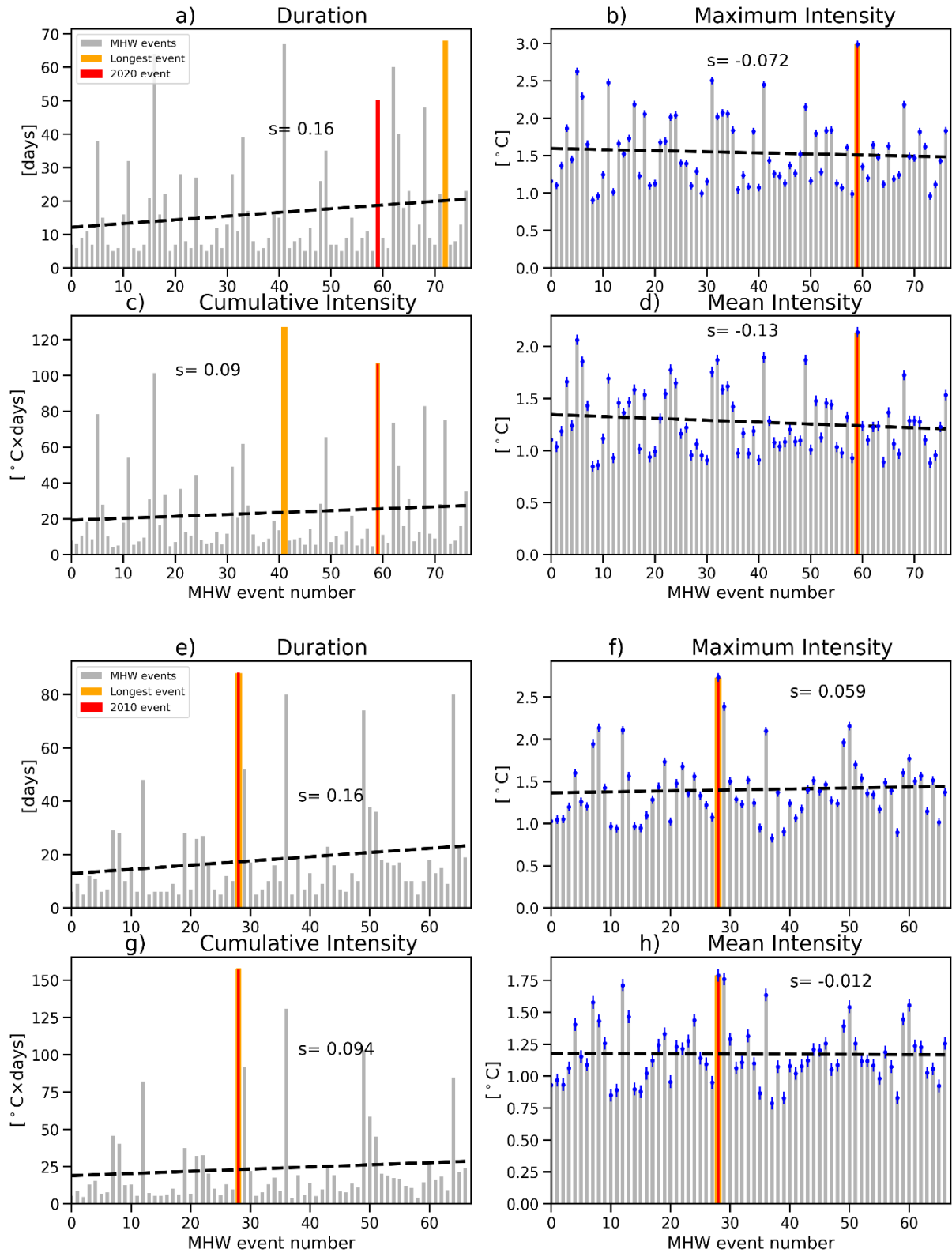


Figure 4.8: MHW properties, including duration, maximum intensity, cumulative intensity and mean intensity in the coastal and open-ocean boxes for the Senegal-Mauritania upwelling system (SMUS).

The latitudinal analysis of MHW episodes shows an increasing trend in the frequency of MHW episodes towards the north (25°N - 18°N), where the persistent of upwelling is more sensitive to the slight increase in SST. However, trends of MHWs were more pronounced in the south (10°N - 14°N), with the maximum and cumulative intensities higher than 5 °C and 200 °C. This pronounced intensity of MHW episodes can be enhanced to the advected warm water driven by the North Equatorial Countercurrent (Faye *et al.*, 2015).

4.2.1.2 MHW Episodes in the GGUS

In the GGUS, MHW episodes were also observed during winter and spring. The number of episodes was around 65 in both coastal and open-ocean boxes. The four main episodes were observed in 1998, 2010, 2018-2019 and 2019-2020, with maximum intensities around 3.10°C in the western (7° - 2°W) along the coasts of Côte d'Ivoire and 2.55 in the eastward (Nigeria coast). The strongest episode was observed from October to march 2020 over the coastal region, with a maximum intensity around 4.0°C (Fig. 4.9a-b), while the longest (145 days) was detected offshore from October 2009 to March 2010, with a maximum intensity 1.8°C (Fig. 4.9c-d).

However, the first episode was recorded on the Nigerian coasts during the first ten days of May 1998, with a maximum intensity of 2.55°C. The second (larger) episode was observed throughout the basin in winter 2010, with a maximum intensity of 1.8°C, and the third was recorded on the Benin-Togo coast between December 2018 and February 2019, with a maximum intensity of 2.5°C. The strongest and longest episode was observed between October 2019 and March 2020 (Figure 4.9), both in the coastal and open ocean, with mean and maximum intensities of 1.62°C and 3.10°C, respectively, and a cumulative intensity of 190°C. This maximum MHW episode was the more widespread episode, affecting almost the entire West African coast. Detail information about the sub-region dynamics of MHW episodes in this region was summarized in Table 4.2.

Table 4.2: Marine heatwave episodes in the coastal and open-ocean boxes over the GGUS.

Region	N_events	Imax	Imean	Icum	Duration	Start date	End date
7 °W - 2°W	87	3.10C	2.17C	207.49C	96 days	04 Nov 2019	08 Feb 2020
2°W – 4°E	97	2.55C	1.81C	90.77 C	48 days	28 Dec 2018	15 Feb 2019

Here again, the majority of the MHW episodes are moderate (93.7%). However, the four largest episodes (1998, 2018-2019 and 2019-2020) are strong in terms of maximum and cumulative intensities (2.5 °C) and duration (145 days, 2019-2020 event). The longitudinal analysis shows a relative increase in MHW days from the east (Nigerian coast) to the west (Ivory Coast). This longitudinal trend can be related to the variability of Atlantic Niño.

Figure 4.10 shows the characteristics of MHW episodes in the GGUS. As in the SMUS region, the result shows that the strongest (red bars) and longest episodes (orange bars) intertwine in duration and cumulative intensities but different in maximum intensities. The linear regression analysis shows increasing trends in all MHW metrics in relation to the evolution of the number of events over time, with an average regression slope around 0.2. These increasing trends in MHW are consistent with global SST trends (Gulev *et al.* 2021).

All the extreme events of MHWs detected in both upwelling regions coincide with the El Niño and Atlantic Niño events. This let suggested that the MHW episodes observed over West African coast are the extreme events of El Niño or Atlantic Niño. However, this affirmation is speculative and need further investigation.

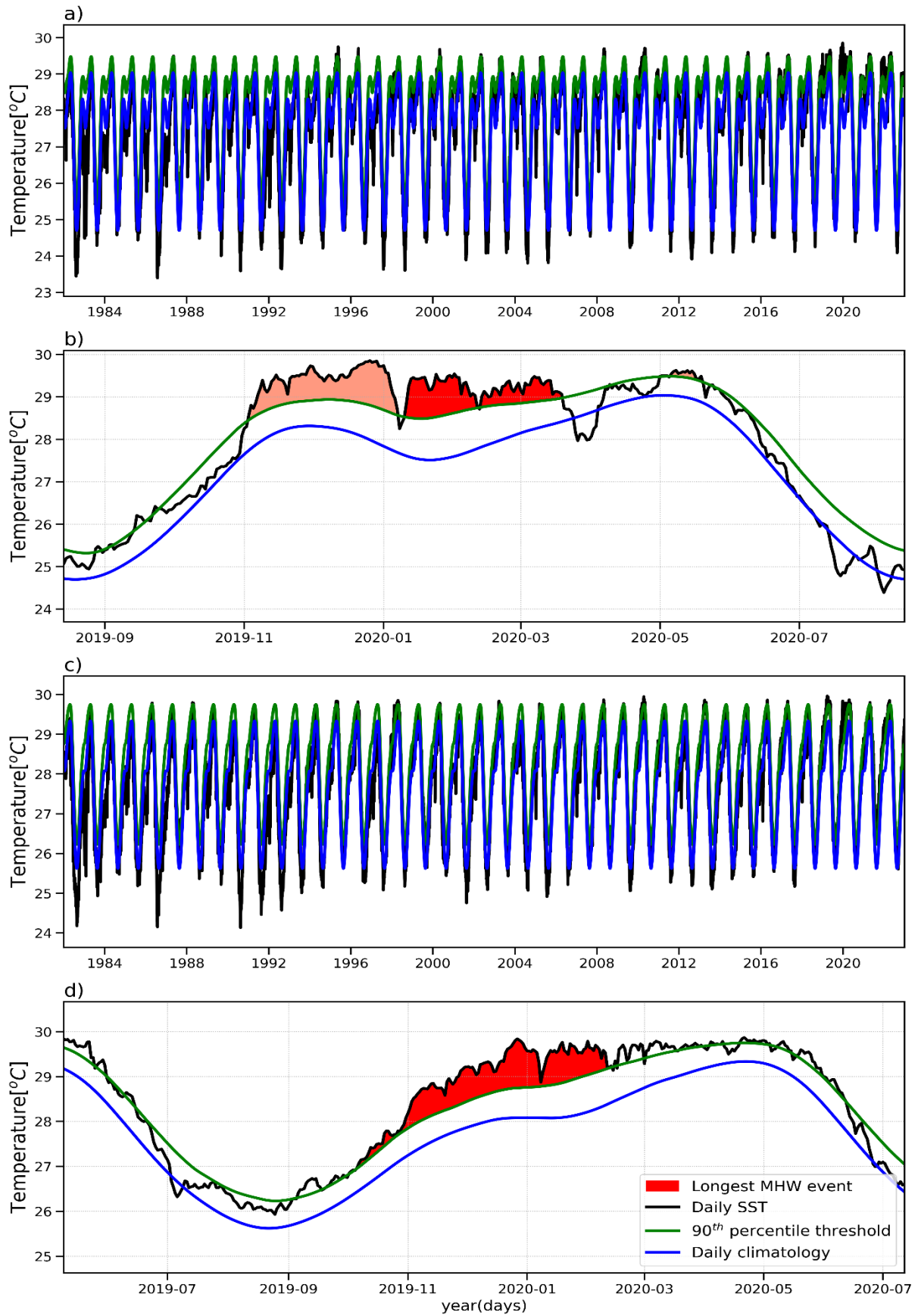


Figure 4.9: a-b SST time series and Strongest Marine heatwave (MHW) episodes in the Gulf of Guinea Upwelling System (GGUS). c-d and time series and Longest MHW.

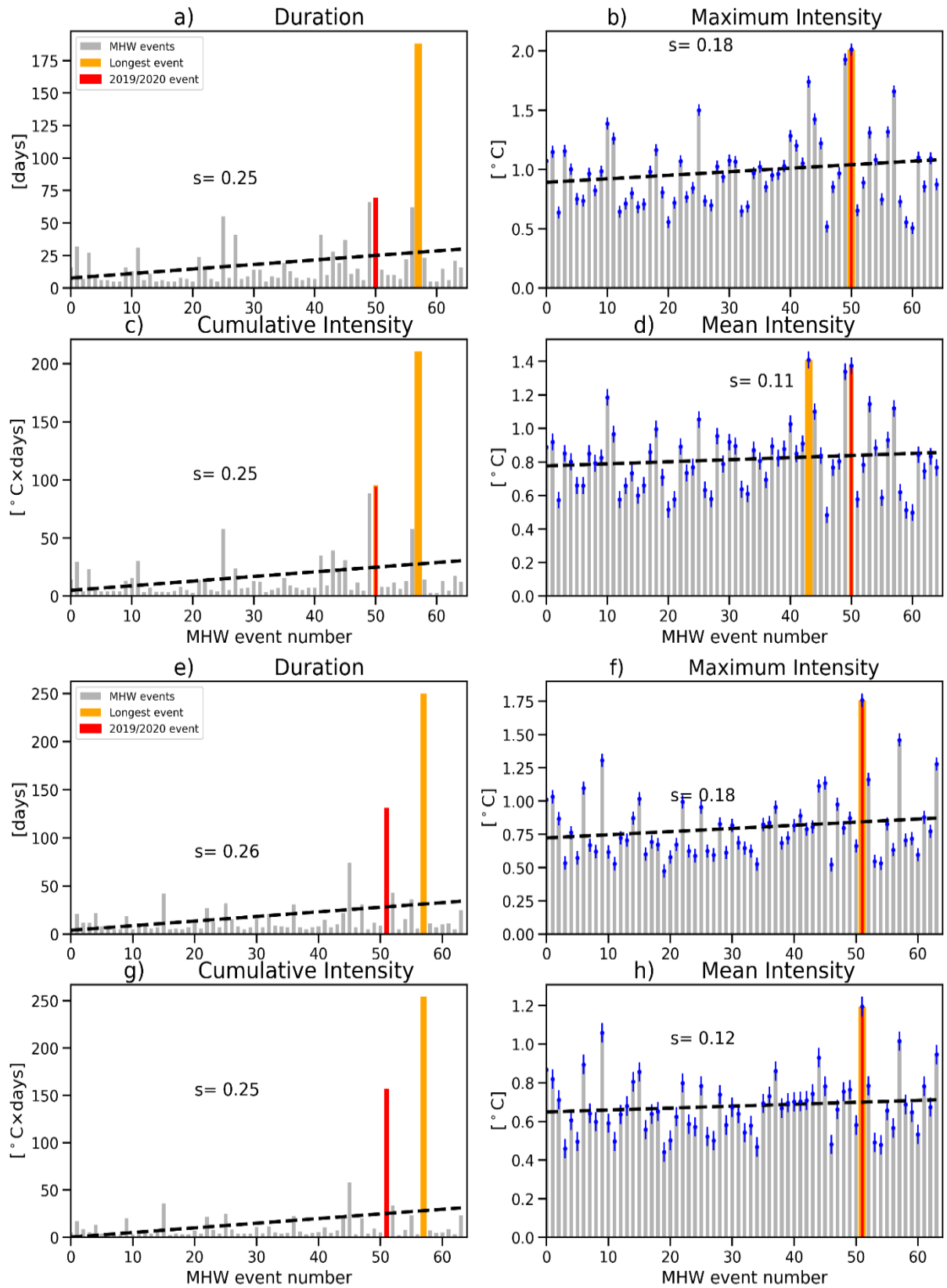


Figure 4.10: Properties of marine heatwave episodes in the coastal (a-d) and open-ocean (e-h) boxes, in the Gulf of Guinea Upwelling System (GGUS) including duration, maximum intensity, mean intensity, cumulative intensity. s is slope of the regression.

4.2.2 Physical Mechanisms as Drivers of Northwest African Coastal MHWs

The potential mechanisms of MHWs along Northwest African coasts were examined using the ocean mixed-layer heat budget terms and the atmospheric surface wind anomalies.

4.2.2.1 Oceanographic Drivers of MHWs in SMUS and GGUS

The ocean temperature tendency was computed in the mixed-layer depth and used to analyze the local drivers of MHW episodes in the Northwest African coastal upwelling systems (Fig.4.11). The temperature tendency include advection, entrainment, surface heat budget and residual terms. The results highlight the relative contribution of each mixed-layer term to the cooling or warming of the ocean surface layer.

The temperature tendency shows that the seasonal warming peaks in summer (July-September) and Fall (September-November), while the seasonal cooling peaks in winter-spring in the SMUS and summer in the GGUS, respectively (Fig 11a-b). This reflects that the mixed-layer terms respond to a seasonal heating and cooling cycles. The temperature tendency of the composite MHW episodes is above the climatology in boreal winter-spring (January-April) and summer (June-September) periods in the SMUS and during the winter period in the GGUS. This indicates that mixed-layer temperature increases faster during MHW episodes.

Advective Processes Influencing MHW Dynamics

Strong cooling due to advection was observed from January to May in the SMUS and June to September in the GGUS (Fig 11c-d), suggesting dynamic processes due to coastal currents such as the NECC and PC in the SMUS, Guinea Current (GC) and NECC in the GGUS, and upwelling mechanisms. During the extreme MHW episodes in the SMUS, cooling by horizontal advection is weaker than the climatology shows a weaker advection cooling than the climatology. Similar patterns were observed in the MHW events in the GGUS. This weakened

advective terms suggests reduced upwelling conditions and altered currents contributing to excess warming.

The entrainment peaks in September in the SMUS and May in the GGUS (Fig 11e-f). MHW composite show slightly reduced entrainment in peak months in the SMUS. In the GGUS, MHW periods show one month shift (June) of the maximum peak and marked suppression of entrainment, especially from July to October. This weaker entrainment indicates less cold water mixed into surface, reinforcing warming.

Surface Heat fluxes Contribution to MHW formation

The surface heat fluxes were observed as MHWs triggers in the Northwest African coastal upwelling ecosystems. The maximum surface heat flux gain was observed in September-November in the GGUS, coinciding with the solar radiation peak. In both upwelling regions, the MHW composite show slight increase of surface heat during winter (January-March). This shows that the maximum MHW episodes coincide with increased solar heat and reducing latent/sensible cooling, but the residual term shows that the surface heat fluxes is not the only driver of MHWs.

In summary, the analysis of mixed layer highlights the key role of ocean currents and a slight contribution of surface heat fluxes in the generation of MHW episodes. It shows the weakening of advection and entrainment during the MHW episodes, and slight increase of surface heat fluxes and residual terms, likely linked to weakening of wind patterns, reduced upwelling and enhanced warming.

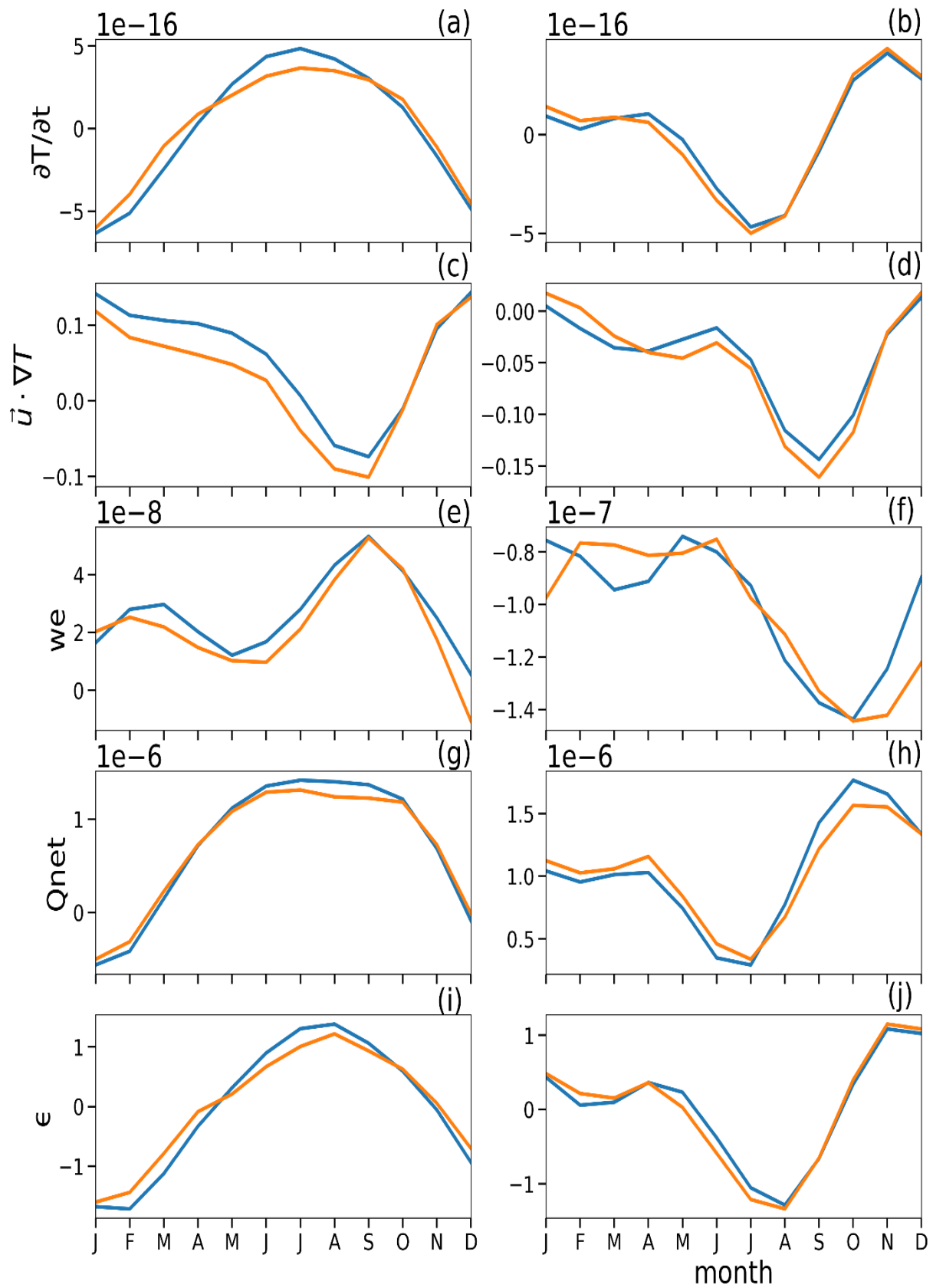


Figure 4.11: Mixed-Layer Heat Budget Terms in the Senegal-Mauritania and Gulf of Guinea Upwelling Systems, including Temperature tendency, Horizontal advection, Entrainment, Surface heat flux and residual term.

In the SUMS, the residual is more positive during the MHW episodes indicating that some unresolved warming exists. The residual is substantially higher during MHW episodes in the GGUS, indicating missing processes such as Kelvin waves, eddies and mixing.

4.2.2.2 Atmospheric Drivers of MHWs in SMUS and GGUS

Wind stress forcing and Ekman dynamics were observed as the primarily drivers of MHW episodes over Northwest African coast. The variability of wind stress forcing, Ekman transport and Ekman pumping were analyzed during the extreme MHW episodes in the Northwest African Upwelling regions. The analysis reveals the strengthening of westerly and northward wind stress associated with enhanced onshore Ekman transport, negative wind stress curl driven and the suppression of upwelling along the Northwest African coast, in particular in the SMUS and GGUS, due to the development of MHW episodes.

Wind stress forcings

The composite analysis of SST and wind stress anomalies during winter-spring over the extremes MHW episodes (Fig. 4.12) show a significant strengthening of westerly and norward winds and weakening of equatorial wind along the Senegal-Mauritania and Gulf of Guinea upwelling regions, respectively. These atmospheric conditions were associated with strong accumulations of warm water along the Senegal-Mauritania and Gulf of Guinea coasts, due to the weakening and reversal of upwelling-favorable winds (equatorward trade wind stress). This strengthening of westerlies seems to be link to the reinforcing of the Azores high pressure systems. The strengthening of westerlies is likely to trap solar heat in surface waters, promoting MHW formation. This process aligns with previous studies (e.g., Smale *et al.*, 2019) that describe how modulations in wind-driven vertical mixing can set the stage for SST anomalies to persist and intensify.

In the GGUS, the composite analysis of wind stress and SST anomalies during the major MHW episodes (Fig. 4.12b) shows a weakening of wind stress over equatorial and coastal regions. This weakening of local wind stress anomalies associated with a relative increase of mixed-layer temperature tendency dominated by advection and surface heat fluxes terms. This suggests the MHW episodes observed in the GGUS are likely driven by the combined effects of the weakening of local and equatorial wind stress the advection warm generated by the regional ocean currents and the local surface heat fluxes of the direct solar radiation. However, the importance of the mixed layer residual term indicates the implications of other mechanisms that required further investigation. Here, the wind stress anomalies could be not considered as the primary driver that modulates SST anomalies and MHWs in this region. Other mechanisms such as advection warm waters generated by the regional ocean currents such as Guinea current (GC) and North Equatorial countercurrent (NECC), surface heat fluxes and other mixed-layer heat budget terms (mixing), equatorial Kelvin waves generated by the remote winds need to be taken to account.

Ekman Dynamics

The composite maps (Figs 4.13 and 4.14) of Ekman transport (arrows) and wind stress curl-driven (shading) anomalies were performed during the extreme MHWs to analyse how previous wind stress anomalies drive MHWs in both upwelling regions. The result shows that the reinforcing of westerly and northward wind stress was associated with enhanced onshore Ekman transport and negative wind stress curl driven, suppressing vertical cooling and the typical coastal upwelling along the Northwest African coast, in particular in the SMUS due to the formation MHWs.

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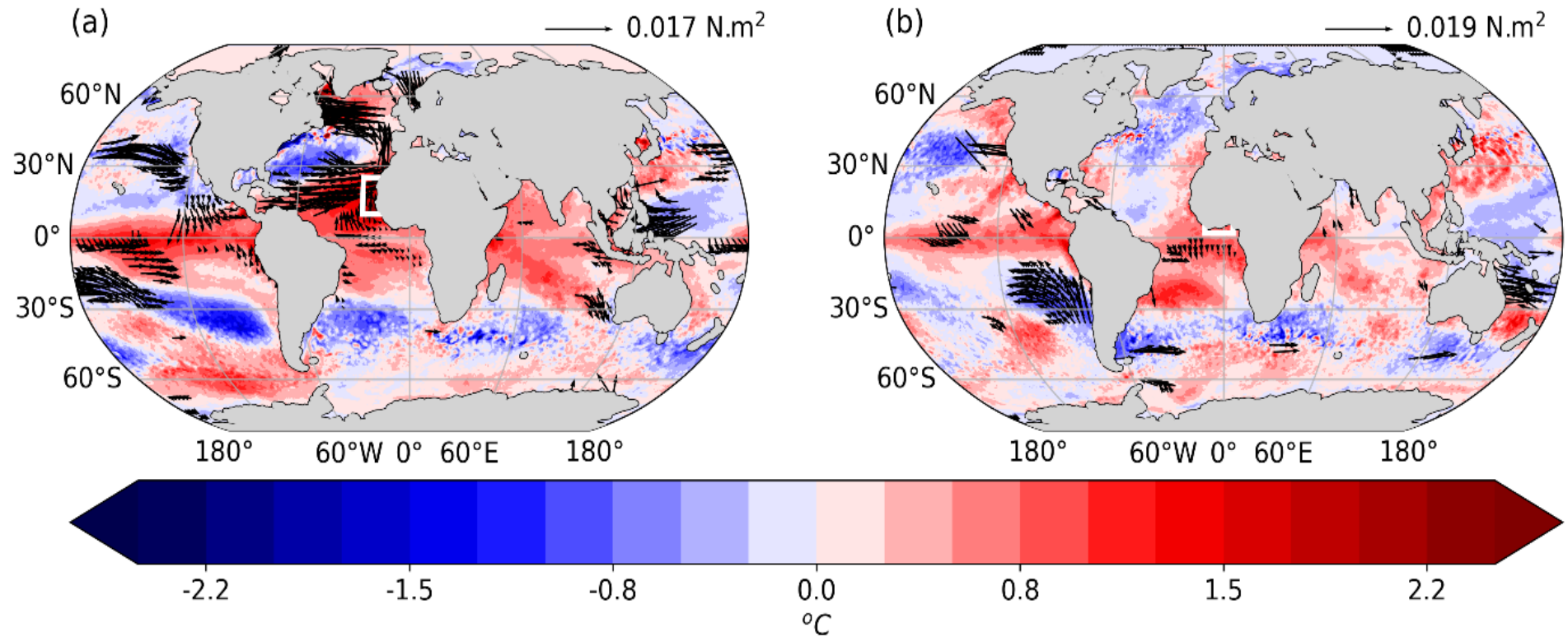


Figure 4.12: a-b Composite anomalies of sea surface temperature (shading) and wind stress (arrows) during the four extreme marine heatwave episodes observed winter and spring (December-May) in the Senegal-Mauritania and Gulf of Guinea upwelling systems, respectively.

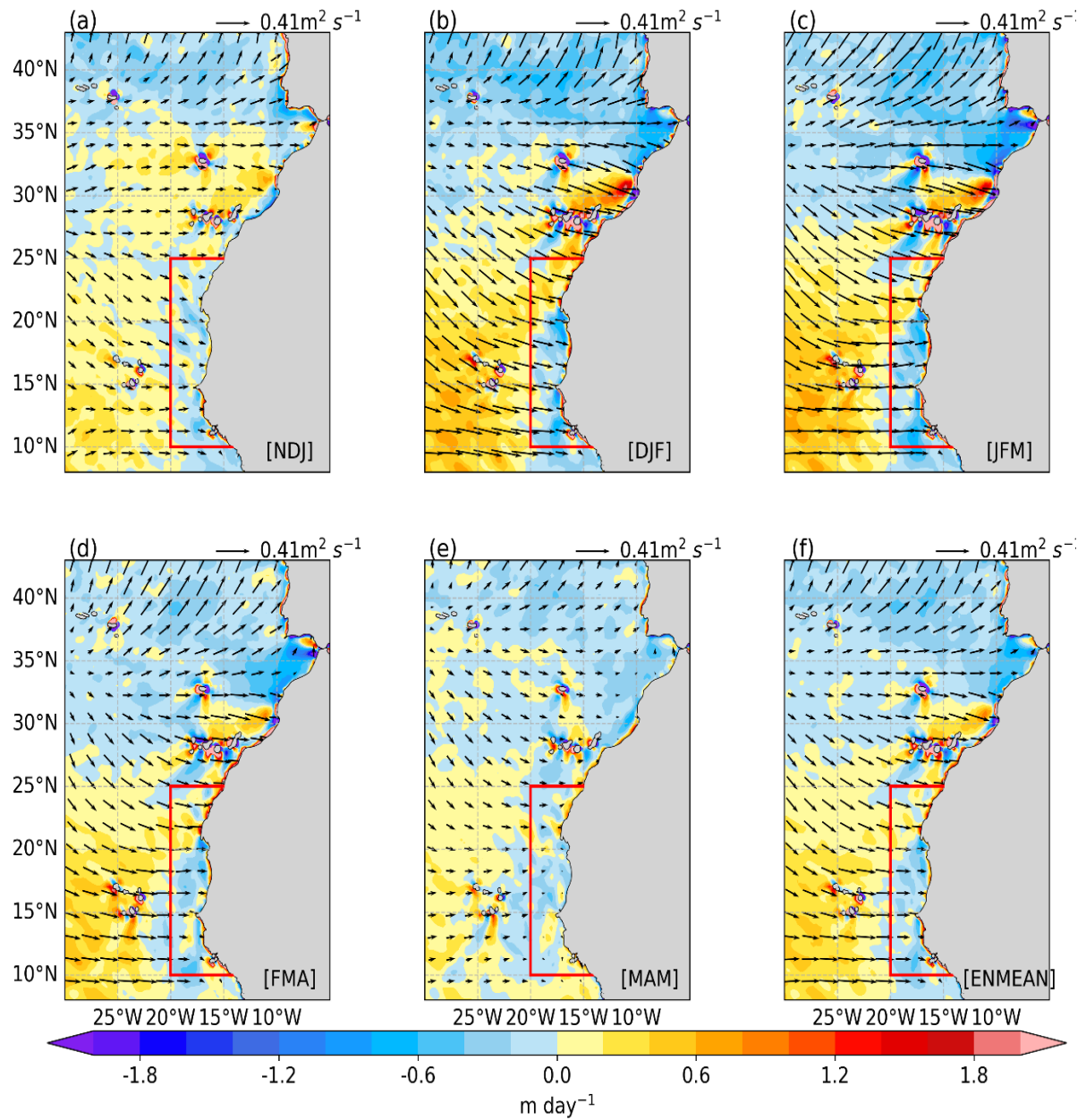


Figure 4.13: Composite maps Ekman transport (arrows) and wind stress curl-driven (shading) during the extreme marine heatwaves (MHWs) observed in winter and spring in the Senegal-Mauritania upwelling region (red boxes).

The seasonal analysis with one-month lag of the composite wind stress behavior in the SMUS shows that the enhancement of onshore Ekman transport and suppression of vertical mixing (wind stress curl-driven), is the resulting observed during December-February (DJF), January-March (JFM) and February-April (FMA), is the resulting of the weakening equatorward wind stress in November-January. These anomalous of Ekman dynamics which weakens surface divergence and vertical pumping, are likely to enhance thermal stratification in the surface layer, reduces the vertical exchange of cool subsurface waters, fostering positive SST anomalies and accumulations of warm water generating MHW events over coastal domains.

This result is consistent with findings from Pastor and Khodayar (2023), who highlight that air-sea coupling mechanisms and regional atmospheric circulation are central to the initiation and maintenance of MHWs in the Mediterranean. Similarly, in our region of study, negative anomalous wind stress curl likely enhances stratification and reduces the vertical exchange of cool subsurface waters (vertical pumping), fostering positive SST anomalies over coastal domains. These findings reinforce that MHWs in upwelling systems are not solely passive responses to global SST trends, but are actively modulated by regional wind dynamics and ocean-atmosphere interactions.

Figure 4.15 shows the Ekman transport (arrows) and wind stress curl driven (shading) of different winter-spring seasons in the GGUS. Similar to the SMUS, strong onshore Ekman transport associated with negative anomalies of wind stress curl, suppressing of upwelling favorable conditions were observed along the North of Gulf of Guinea coastal region. Here, the persistent onshore Ekman transport and negative wind stress curl observed during major MHW episodes plays a dual role: it inhibits the vertical transport of cold water and enhances surface layer stratification, creating conditions conducive to heat accumulation.

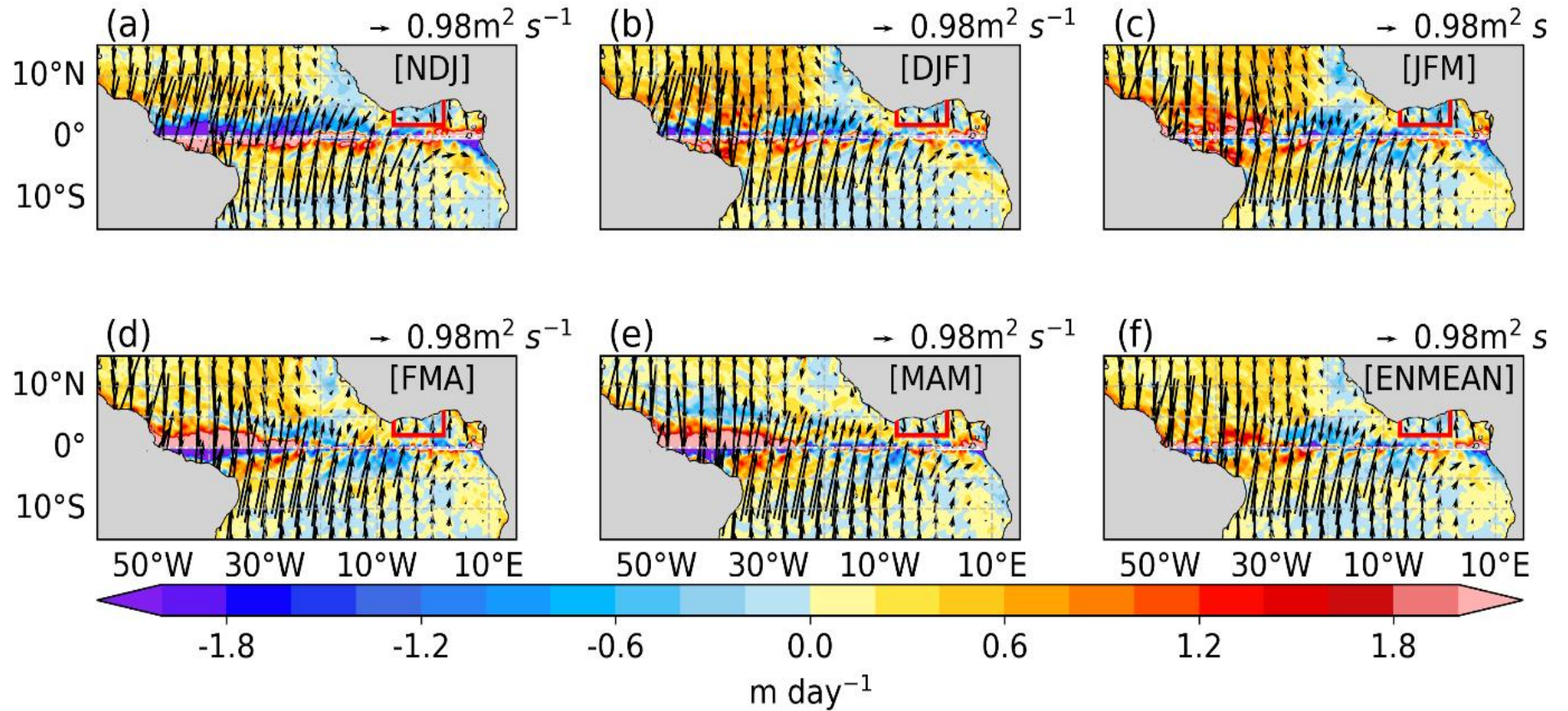


Figure 4.14: Composite Ekman transport (arrows) and wind stress curl-driven (shading) during the extreme marine heatwaves (MHWs) in winter and spring in the Gulf of Guinea upwelling region (red boxes).

The observed cross-shore wind anomalies enhance onshore Ekman transport, directly opposing the offshore surface flow necessary for upwelling. Moreover, the negative anomalies in wind stress curl further inhibit Ekman pumping, reducing vertical velocity and upward flux of cooler waters. These mechanisms together establish the oceanic preconditions favourable for MHW development was supported by the work of Darmaraki *et al.*, (2019a, b), who showed that Mediterranean MHWs are increasingly associated with weakened vertical exchange processes, driven by regional atmospheric circulation changes.

4.2.2.3 SST-Wind Stress Coupling as Coastal MHW Drivers in SMUS and GGUS

As the major MHW episodes were observed during the peaks of ENSO events, the regression analyses were performed between wind stress and SST anomaly fields, and ENSO index, in particular Niño 3.4. The regression maps obtained between wind stress anomalies and Niño 3.4 index during the major MHWs (Fig. 4.15) show significant relationship between both patterns.

Positive regression coefficients were observed in winter (DJF) and spring (MAM) between the anomalies of wind stress fields and Niño 3.4 along the Senegal-Mauritanian coast (Fig. 4.15a-d). These positive regression coefficients were significantly important with meridional wind stress anomalies than zonal wind stress. This result suggests a good connection between ENSO extreme events and the coastal variability of wind stress likely to drive the thermal stratification over Senegal-Mauritania coast as mentioned by Oettli *et al.* (2016) and Wade *et al.* (2023). In the GGUS, the positive regression coefficients were significant only with the zonal wind stress anomalies (Fig. 4.15g-h). The regression coefficients with the meridional wind stress are negatives and close to zero. This result suggests that the thermal stratification during the extremes temperature events in the GGUS could be coupled the zonal wind stress anomalies.

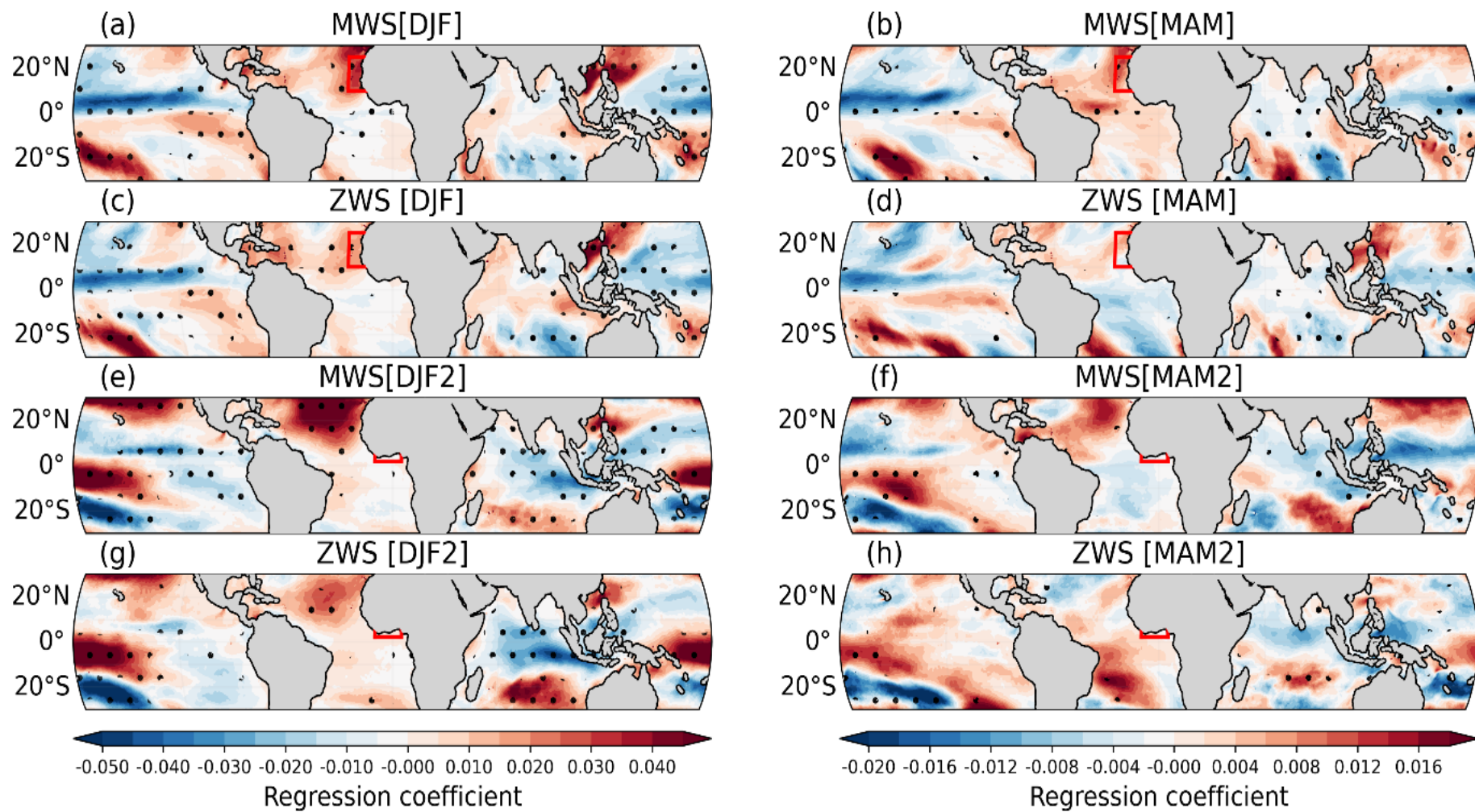


Figure 4.15: Regression maps between wind stress anomalies and Niño 3.4 index during extreme MHW events in the Senegal-Mauritania and Gulf of Guinea upwelling systems (red boxes) with significant regression (p-value=95%).

Figures 4.16 and 4.17 present regression maps illustrating the coupled variability of SST anomalies associated with the leading modes (PC1 and PC2) of surface wind stress (shading), and between wind stress anomalies associated with SST leading modes over the SMUS and GGUS during the extreme MHW events. The results reveal clear spatiotemporal patterns in the coupling between SST and surface wind stress anomalies during MHW episodes across the SMUS and the GGUS. The regression analyses using leading PCs of meridional and zonal wind stress highlight regionally distinct mechanisms controlling the onset and persistence of extreme warm events. Each panel shows regressions over various seasons and lags, indicating how wind anomalies pre-cede (Lag -1) or co-occur (Lag 0) with SST patterns, and vice versa. The SST anomalies were performed with each wind stress component in each upwelling region but only the significant regression wind stress component is showing in the main text. Others are in the Appendices section (Figs A3, 4).

Over the SMUS (Fig 4.18), SST anomalies exhibit a strong inverse relationship with meridional wind stress anomalies. Specifically, weakened equatorward winds during boreal winter to early spring (NDJ to MAM) are closely linked with positive SSTAs, both in lagged and concurrent regressions. This pattern is consistent with a reduction in upwelling-favorable winds, leading to suppressed vertical nutrient supply and surface ocean warming (Capet et al. 2017, Kounta et al. 2018). The contemporaneous regression patterns (lag 0) confirm coupled ocean-atmosphere feedback wherein positive SST anomalies are associated with anomalous poleward winds, further inhibiting upwelling. These results underscore the primary role of meridional wind anomalies in modulating MHW occurrence and intensity in this region, particularly during the peak upwelling season (FMA-MAM). While meridional winds are the main modulators of SMUS SST variability, zonal wind stress anomalies also contribute, albeit to a lesser extent. Regressions between SST and the leading PCs of zonal wind stress show that weakened easterlies or mild westerly anomalies over the subtropical northeast Atlantic during DJF-FMA

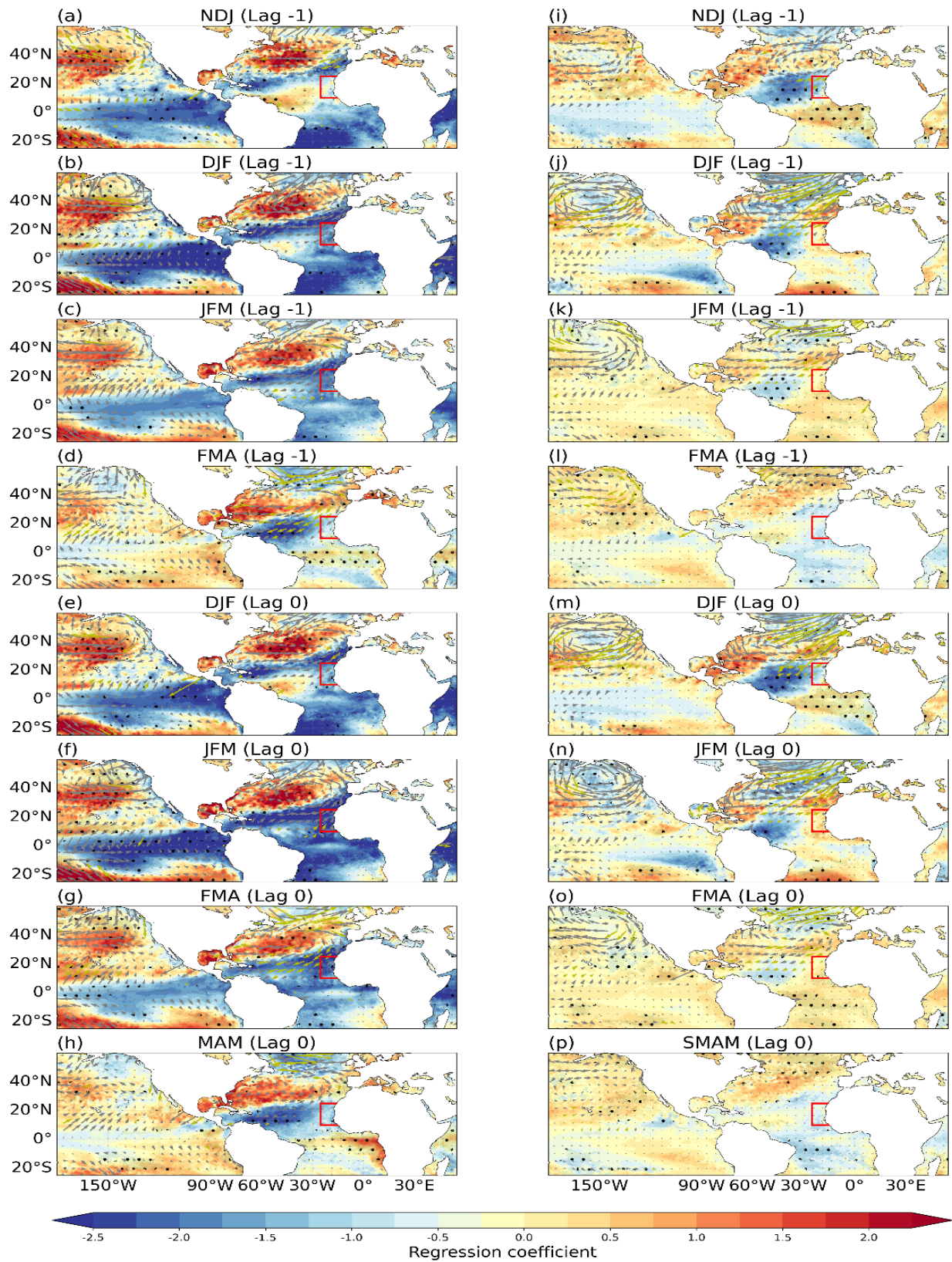


Figure 4.16: Regression maps between global SST and meridional wind stress anomaly fields and leading modes during the extremes MHW episodes in the Senegal-Mauritania coastal upwelling system (red boxes).

are weakly associated with SST warming along the Northwest African coast. This suggests a potential role of horizontal advection or altered Ekman transport from the ocean interior toward the coast. However, the spatial coherence and strength of this relationship are less robust than those observed for meridional winds, indicating a secondary, modulating influence.

In contrast to SMUS, the GGUS (Fig 4.17) is more sensitive to zonal wind stress anomalies, particularly over the equatorial Atlantic. Regression analyses reveal that the zonal component of wind stress plays a more influential role than the meridional component in driving extreme SST anomalies, such as marine heatwaves. The regression maps show that positive SST anomalies in the GGUS tend to follow weakened easterly or anomalous westerly wind patterns along the equator particularly during boreal winter and spring (DJF-FMA) associated with the first principal component of zonal wind stress (ZWS-PC1). These zonal wind changes significantly inhibit or suppress equatorial upwelling and promote eastward advection of surface warming water via Kelvin waves and surface currents (Djakouré *et al.*, 2017). The coupling is especially strong during El Niño-like conditions, which are known to project onto zonal wind stress anomalies over the equatorial Atlantic. This effect is further reinforced by positive feedbacks, where warm SSTs induce westerly wind anomalies, consistent with Bjerknes-like dynamics observed during Atlantic Niño events.

Across both systems, SST anomalies and wind stress patterns exhibit signs of retroaction, particularly at lag 0. This suggests that once initiated, SST anomalies during MHWs may feedback onto atmospheric circulation by altering the thermal gradients between the continent and ocean, thereby modulating wind stress fields. For instance, anomalous warming may suppress the land-sea pressure contrast, further weakening upwelling-favorable winds and enhancing MHW persistence. This coupled feedback mechanism likely reinforces the intensity and duration of warm events.

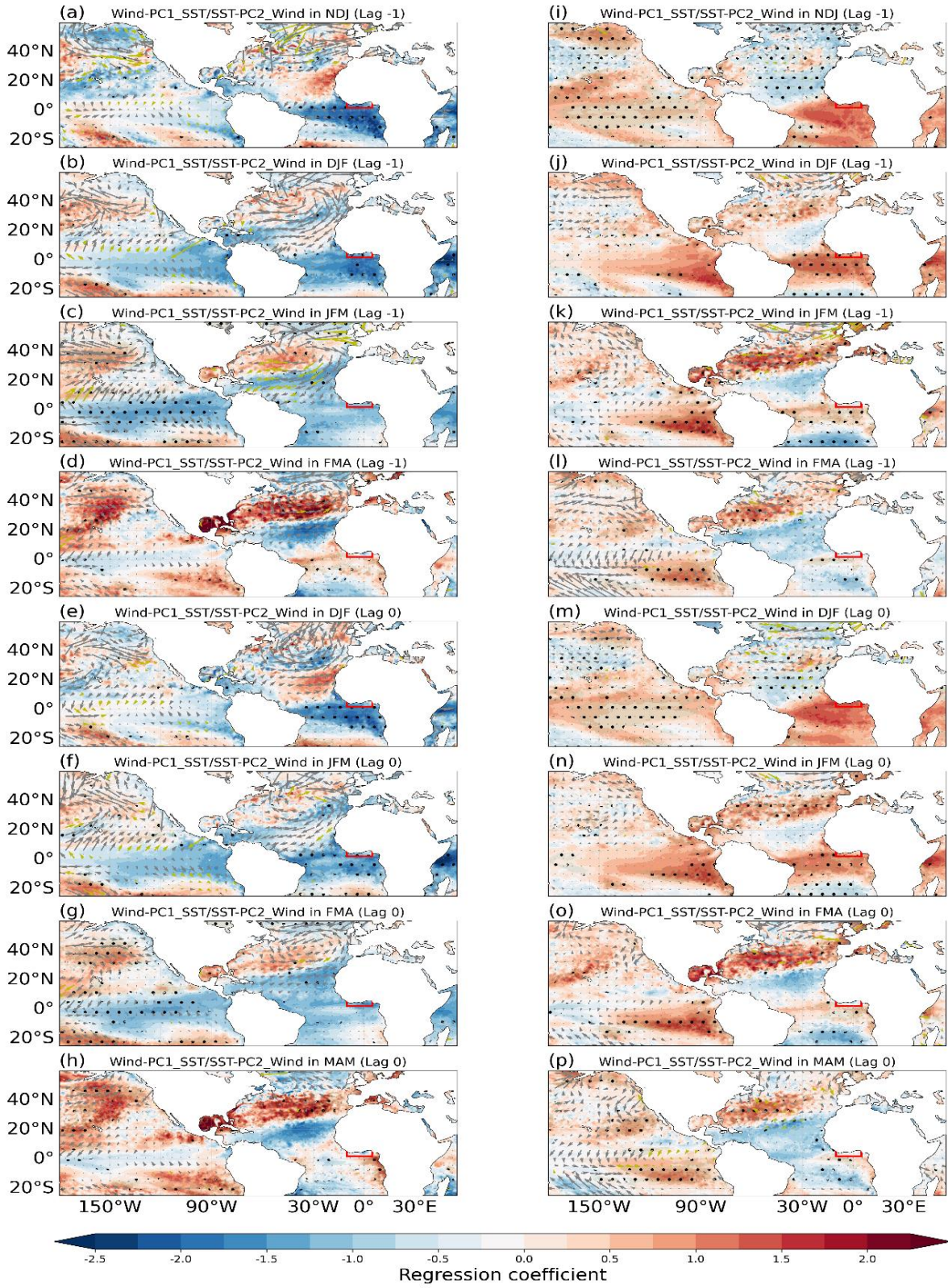


Figure 4.17: Regression between global SST and zonal wind stress anomaly fields and leading modes during the extreme MHW episodes in the Gulf of Guinea coastal upwelling system (red boxes).

Wavelet coherence analysis of SST and wind stress (WSA) anomalies during MHW events (Fig 4.18) reveals insights into the temporal and frequency-dependent coupling of atmosphere-ocean interactions in the Senegal-Mauritania and Gulf of Guinea coastal upwelling systems. In the Senegal-Mauritania region (Fig 4.18a-c), strong coherence is observed at timescales ranging from interseasonal to interannual, particularly between two and six months and around one year. This indicates that both local wind-driven processes and remote influences modulate SST variability during MHW episodes. The in-phase relationship, as indicated by phase arrows pointing to the right, suggests that periods of anomalously weak upwelling-favorable winds coincide with positive SST anomalies, promoting heatwave conditions. Conversely, anti-phase relationships and lead-lag signals suggest the potential influence of remote forcing or delayed oceanic responses, such as subsurface warming or heat content redistribution. In the Gulf of Guinea upwelling system (Fig. 4.18), the coherence pattern is more pronounced at semi-annual and interannual timescales. This reflects the influence of equatorial wind variability and large-scale modes, such as the Atlantic Niño. Phase analysis in this region suggests that SST anomalies often lag behind wind anomalies. This highlights the importance of oceanic wave dynamics, particularly equatorial Kelvin and Rossby waves, in modulating the coastal thermocline and surface warming. These findings underscore the critical role of wind anomalies in triggering or modulating marine heat waves and highlight the importance of remote ocean-atmosphere interactions, particularly in equatorial regions where dynamical processes operate across broader spatiotemporal scales.

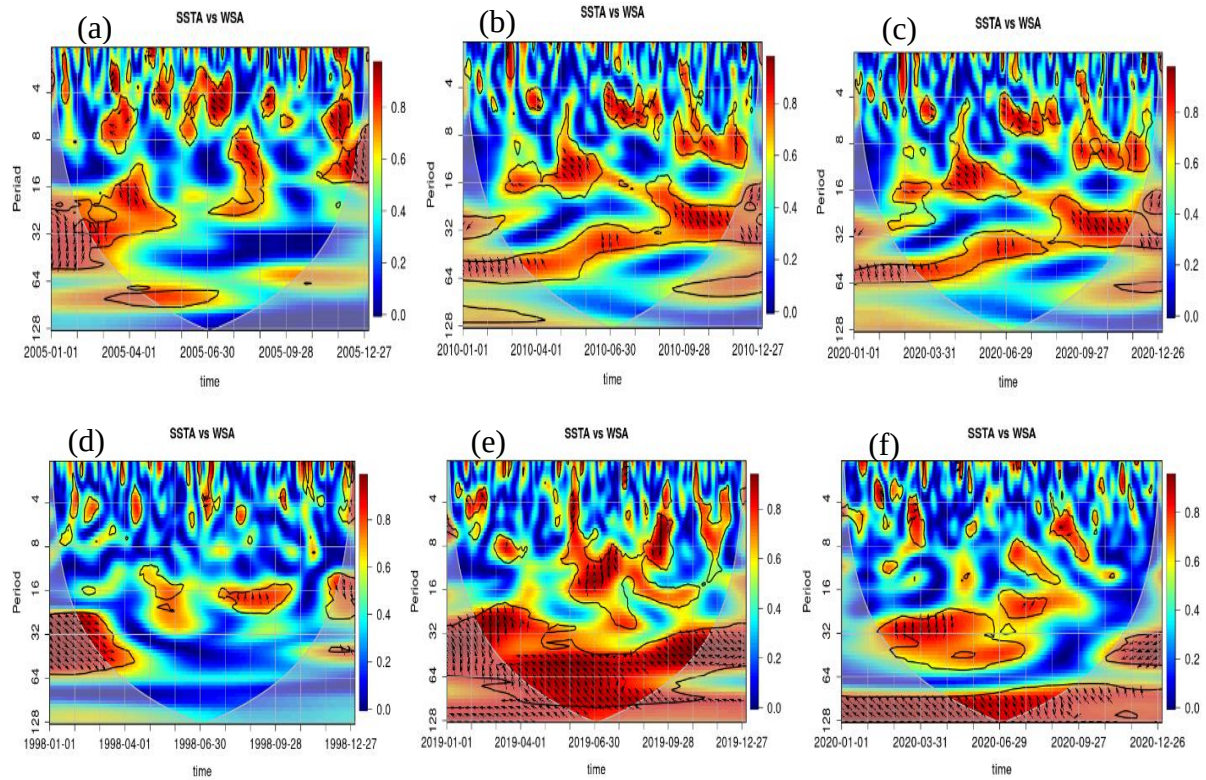


Figure 4.18: Wavelet spectrum showing the coherence between SST and Wind speed anomaly (WSA) signals during the extremes MHW episodes in the Senegal-Mauritania and Gulf of Guinea upwelling regions.

4.2.2.4 Implications and Vulnerability of Upwelling Zones

The MHW episodes can drive substantial changes in upwelling features and productivity. In the SMUS, productivity and surface cooling are tightly linked to wind-driven Ekman divergence due to its sharp thermal gradients and dynamic surface layer. The weakening of wind stress curl, for instance, reduces Ekman suction (upward motion), which is normally a key mechanism for nutrient delivery and surface cooling in the SMUS.

The persistence of positive SST anomalies resulting from weakened upwelling creates feedback loops warmer SSTs reduce wind stress via stabilization of the boundary layer, further weakening upwelling (Frölicher *et al.*, 2018; Oliver *et al.*, 2018). This reinforces our observed mechanism and underlines the sensitivity of EBUS to short-term wind anomalies, which are capable of initiating long-lasting MHW events. In contrast, upwelling can moderate the effects of MHWs reducing its intensity as demonstrated by et Varela *et al.*, (2021).

The suppression of upwelling by MHWs can drive ecological vulnerability and predictive implications, reducing nutrient input to surface waters and diminishing primary productivity. This can also disrupt food webs, fisheries, and biodiversity in this one of the world's most productive marine ecosystems.

In partial summary, the results of these analyses demonstrated that MHW episodes in the Northwest African coast, in particular in the coastal upwelling regions are primarily driven by the atmospheric forcings (wind stress, Ekman dynamics), and modulated by ocean circulation and ocean-atmosphere interactions. This study investigates the drivers of MHWs in the Senegal-Mauritania and Gulf of Guinea upwelling systems, highlighting the role of local atmospheric forcing and large-scale climate variability. Using the standardized methodology of Hobday *et al.*, (2016, 2018), we ensured that the detected MHWs represent statistically robust deviations from historical norms, strengthening the reliability and comparability of our results.

Wind-driven dynamics and upwelling suppression Our results indicate that coastal MHWs along Northwest Africa are mainly shaped by wind-driven changes in Ekman transport and vertical mixing. Stronger westerlies and northerlies, especially during El Niño events, disrupt typical upwelling by enhancing onshore Ekman transport and weakening wind stress curl. This suppresses vertical cooling, promotes surface heat retention, and increases ocean stratification, key processes underlying MHW formation. These observations are consistent with previous studies such as Pastor and Khodayar (2023), who reported that persistent anticyclonic conditions and weakened winds drive MHWs by inhibiting entrainment and reducing latent heat flux loss in the Mediterranean.

While local dynamics are important, our results also support the modulation of regional wind anomalies by large-scale climate modes. This is consistent with Holbrook *et al.*, (2019) and Sen Gupta *et al.*, (2020), who emphasize the influence of climate oscillations-including ENSO, NAO, and SOI on MHW variability through their effects on wind stress and heat fluxes. For example, the influence of ENSO and SOI on the Bay of Bengal (Kumar *et al.*, 2023) reflects the modulation of wind-driven upwelling along northwest Africa. These links suggest that the regional atmospheric anomalies observed in our study may be embedded in broader patterns such as the North Atlantic subtropical ridge or tropical Atlantic teleconnections.

The mechanisms identified in this study reflect broader patterns observed in other eastern boundary upwelling systems (EBUS). As highlighted by Smale *et al.*, (2019), MHWs arise from a combination of local air-sea fluxes, ocean advection, and teleconnections. In the East Asian marginal seas, Oh *et al.*, (2023) and Lee *et al.*, (2023) identified reduced vertical mixing, Ekman downwelling, and persistent anticyclonic circulation as key MHW drivers-dynamics similar to those we observed off northwest Africa. These studies show that suppressed entrainment and enhanced stratification driven by wind anomalies are common precursors of coastal MHWs in semi-enclosed basins and boundary current systems.

Benthuisen *et al.*, (2020) similarly emphasize the importance of regional-scale atmospheric drivers, such as weakened winds, reduced latent heat fluxes, and reduced mixing, in shaping MHW behaviour in the Mediterranean. Our results are consistent with this synthesis: the reduced Ekman suction and enhanced coastal stratification we observe reflect the same processes highlighted in boundary current systems globally. As shown by Darmaraki *et al.*, (2019a, b), such stratification-enhancing conditions can reduce vertical heat exchange and prolong marine heat extremes, highlighting the vulnerability of EBUS to MHWs.

In addition to atmospheric forcing, mesoscale oceanic features such as eddies also modulate MHWs by altering SST variability. Bian *et al.*, (2023) found that eddies can intensify MHWs, particularly in regions where mesoscale activity intersects with upwelling zones. These interactions can enhance the persistence and spatial footprint of MHWs, particularly in regions such as northwest Africa, where coastal geometry and shelf width enhance local ocean-atmosphere coupling. He *et al.*, (2023) further emphasize on the importance of MHW mobility, where warm anomalies were found to propagate via alongshore or cross-shelf advection, potentially sustaining or amplifying MHW events. Our results suggest that remote thermal anomalies, possibly originating from adjacent tropical waters, could interact with wind-driven processes to intensify coastal heat extremes.

The ecological consequences of MHWs extend beyond thermal anomalies. Smale *et al.*, (2019) and Belkin and Short (2023) document widespread biodiversity loss, altered species composition, and disruption of ecosystem services such as fisheries and carbon sequestration. Such disruptions could be particularly severe in upwelling regions such as northwest Africa, where biological productivity is closely linked to cold-rich nutrient water upwelling. Prolonged MHWs can trigger trophic shifts, reduce fisheries yields, and threaten food security and local economies. Dalsin *et al.*, (2023) emphasize that these effects may persist long after MHWs

subside, underscoring the need for early warning systems and adaptive management strategies in vulnerable regions.

4.2.3 Change of Coastal upwelling Dynamics during MHW Episodes

In this section, the comparison analyses of upwelling indices based on Ekman dynamics and SST gradients were used to analyse the sensitivity of coastal upwelling activities to the MHW events. In each upwelling region, statistical changes in upwelling metrics (timing, intensity and duration) and productivity were observed during the extreme episodes of MHWs.

In the SMUS, the comparison between the climatology and the composite maps of extreme MHWs of the zonal Ekman transport and SST gradient (Fig. 4.19) shows a weakening of upwelling intensity during December-May due to the weakening of upwelling favourable winds (equatorward trade winds). The difference of Ekman transport (Fig. 4.19a-c, shading) observed between the climatological mean computed over the study period (Fig 4.19a) and the extreme MHW episodes (Fig 4.19b) is about $0.5 \text{ m}^2 \text{ s}^{-1}$ from January to March (Fig. 4.19c). However, changes in the wind stress curl-driven were not significant.

The SST patterns (Fig. 4.19c-d) shows an increase in SST anomalies during winter and spring, suppressing the upwelling signal in the southern of upwelling region (10° - 14° N), with a poleward migration of the upwelling current. The SST difference between the climatology and the extreme MHW episodes (Fig 4.19e) reaches $+2^{\circ}\text{C}$ from February to May, with a decrease trend of upwelling signal of about -0.5°C (Fig. 4.19f). These changes in the upwelling index are likely to have significant impacts on coastal ecosystems, as has been observed elsewhere (e.g., Frölicher and Laufkötter 2018, Oliver et al. 2018a, Smale et al. 2019).

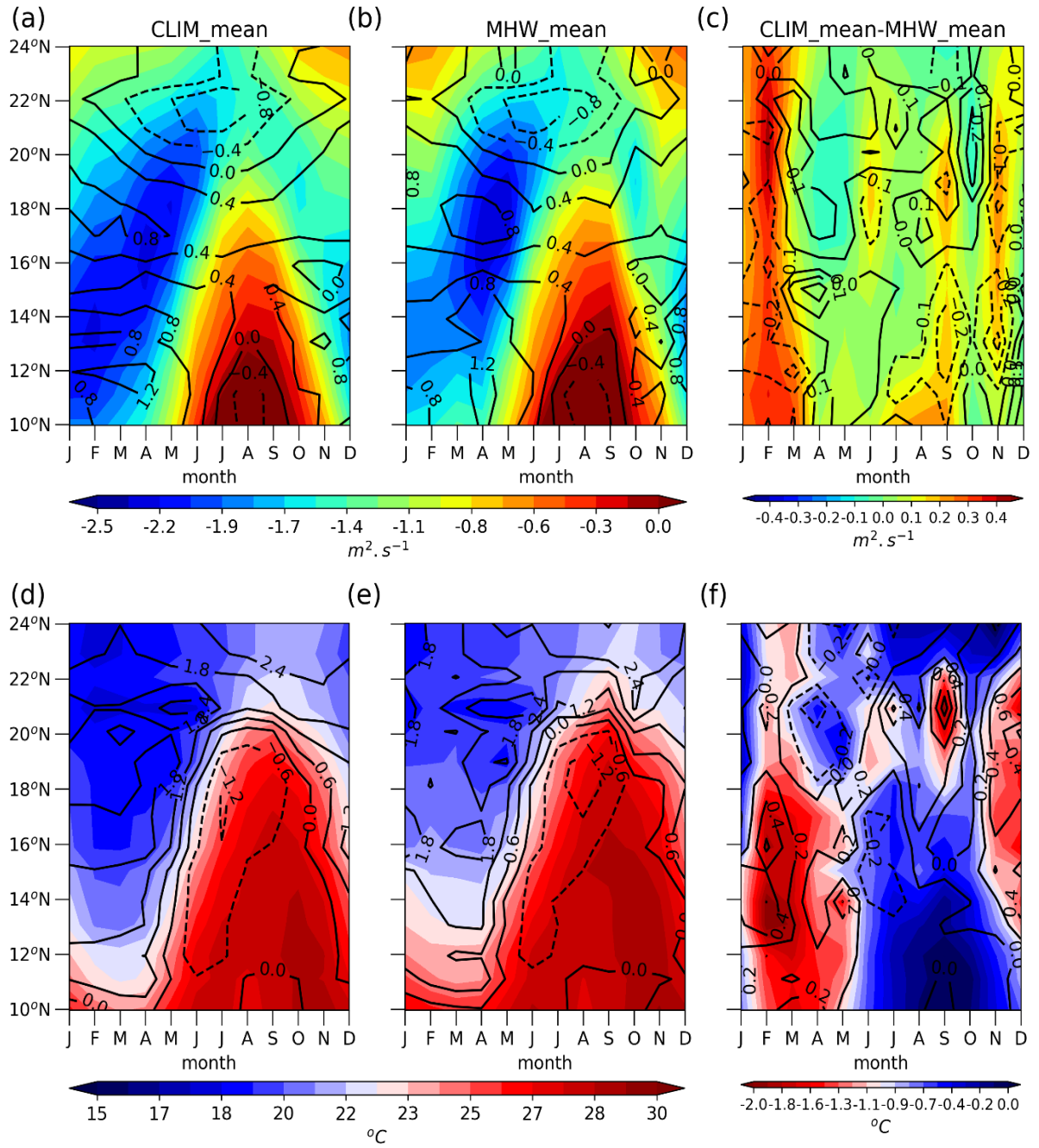


Figure 4.19: Upwelling index based on Ekman dynamics (a-c) (Ekman transport and wind stress curl-driven) and SST patterns (d-f) in the Senegal- Mauritania Upwelling System (SMUS).

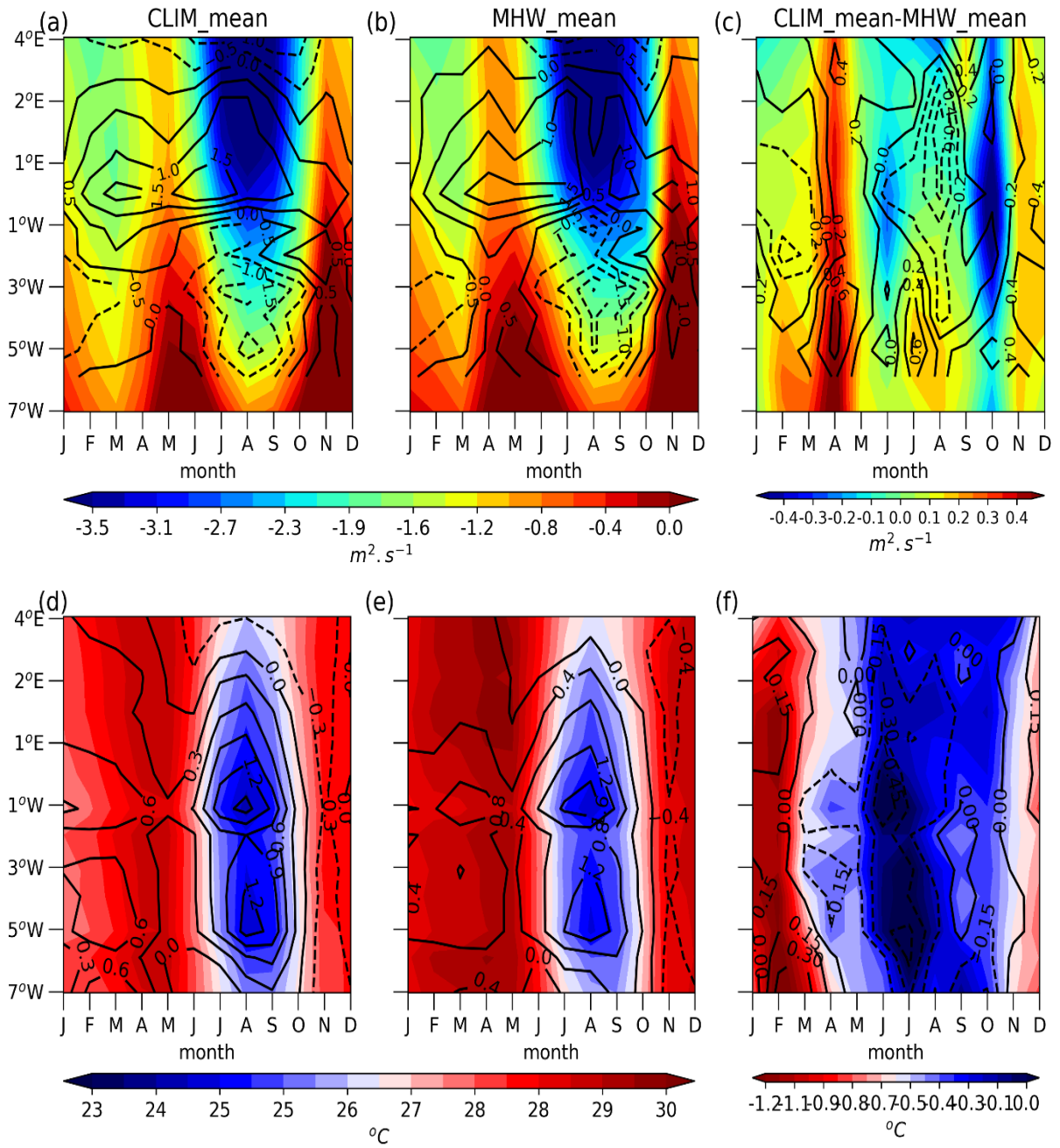


Figure 4.20: Upwelling index based on Ekman dynamics (a-c) (Ekman transport and wind stress curl- driven) and SST patterns (d-f) in the Gulf of Guinea coastal Upwelling System (GGUS).

Figure 4.20 illustrates the annual cycles of meridional Ekman transport and wind stress curl driven (Fig 4.20a-c), SST and SST-based upwelling index (Fig. 4.20d-f) in the Gulf of Guinea coastal upwelling box. The comparative analysis between the climatology and the composite of MHW episodes shows a seasonal decrease trend of the meridional Ekman transport and increase trend of SST which peaks in February-March. These winter and spring changes in SST and Ekman transport do not show a significant impact on the following summer coastal upwelling features.

4.2.4 Impacts of MHW on Northwest African Coastal Upwelling Ecosystem Productivity

The monthly average and standard deviation of chlorophyll-a (Chl-a) concentration were used to analyse the seasonal and spatial changes in coastal ecosystem primary productivity in the SMUS and GGUS, due to the extreme MHW events.

The seasonal comparison between the climatology and the composite of extreme MHW episodes shows important increase in Chl-a over the year in the coastal upwelling band (Fig. 4.21a). This increase trend was more pronounced in the strong cooling region such as between 18-22°N and 12-14°N, where upwelling seems to be almost permanent, but with a weak seasonal variability (Fig 4.21b). In contrast, the temporal upwelling region show a decrease and disappearance of Chl-a because of the suppression coastal upwelling. The peaks of Chl-a concentration were observed from February to December, especially in permanent upwelling regions and correspond to the slight increase of cooling water temperature favourable to the Chl-a concentration. The standard deviation show that the maximum variability of Chl-a was increase of 1 mg.m⁻³ (Fig 4.21f). The difference between climatological and MHW conditions (Fig. 4.21c) reveals widespread negative Chl-a anomalies across 12°N-22°N from February to June. This spatial and temporal pattern suggests that MHWs significantly suppress primary

productivity by weakening upwelling-driven nutrient delivery, likely due to enhanced upper ocean stratification and thermocline deepening (Oliver *et al.*, 2018; Jacox *et al.*, 2020).

The spatial distribution of Chl-a concentrations under MHW conditions (Fig. 4.21d) highlights high interannual disparities. During MHW events (Fig. 4.21e-f), the Chl-a pattern of variability decrease spatially in the regions influenced by coastal upwelling such as the central SMUS (~16°-20°N), suggesting that MHWs dampen phytoplankton responses to upwelling variability, possibly by imposing a persistently stratified upper ocean state. In some southern regions, increased variability may reflect sporadic or localized productivity events.

A closer examination of the peak upwelling season (December-May, Fig. 4.21g-i) further supports the suppressive role of MHWs on coastal productivity. Climatological Chl-a averages (Fig. 21g) are highest along the nearshore zones from 12°N to 24°N, reflecting robust nutrient inputs. During MHWs (Fig. 4.21h), these concentrations decrease sharply, especially near Cap Blanc and the southern SMUS. Black dots indicating statistically significant differences highlight that the productivity decline is not only spatially extensive, but also robust. The standard deviation patterns (Fig. 4.21i-j) confirm a general decrease in productivity variability during MHWs, especially in the core upwelling zones.

These results provide strong evidence that MHWs negatively affect the intensity and spatial extent of upwelling-driven productivity in the SMUS. Given that this region supports important pelagic fisheries and is a major contributor to regional carbon export, the observed reductions in Chl-a during MHWs may have cascading effects across trophic levels and on biogeochemical cycling. Our results highlight the vulnerability of Northwest African coastal upwelling ecosystems to thermal extremes, particularly under the projected increase in frequency and duration of MHWs due to climate change (Frölicher *et al.*, 2018).

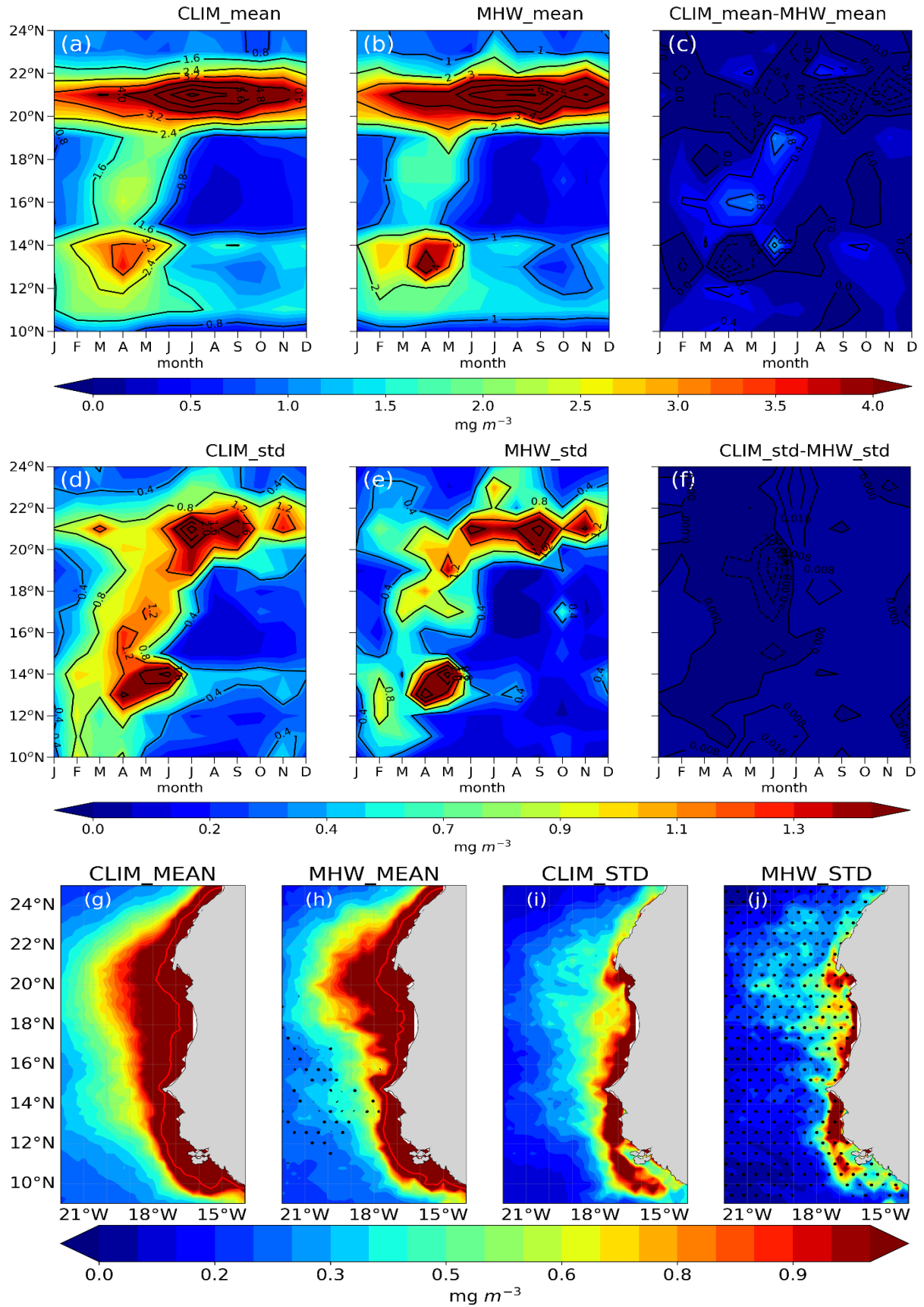


Figure 4.21: Composite analysis of Chlorophyll-a (Chl-a) concentration (mg m^{-3}) during the extreme MHW episodes in the Senegal-Mauritania Upwelling System (SMUS).

4.2.5 Influence of MHW Episodes on the Regional Hydroclimate

This section examines the impacts of extreme MHW events on the hydroclimatic conditions of West Africa, focusing on seasonal anomalies in precipitation and surface air temperature. The analysis is based on spatial composites corresponding to MHW periods and is interpreted in light of established knowledge of West African Monsoon dynamics.

Figure 4.22 illustrates the spatial and seasonal distributions of precipitation anomalies (shading, in mm day^{-1}) and surface air temperature anomalies (red contours) over West Africa during extreme MHW events. The hydroclimatic response reveals strong seasonality and marked asymmetry, reflecting variations in ocean-atmosphere coupling and monsoon dynamics across seasons. The seasonal and latitudinal distribution show a strong monthly drop of the amount local precipitation over West African coast during the major MHW episodes. In the Sahel region ($10\text{--}21^\circ\text{N}$), particularly in the SMUS, the maximum monthly precipitation decreased from 210 mm in August (climatology) to 22 mm (MHW composite), (89.5% of drop). Meanwhile, maximum total precipitation in the Gulf of Guinea, particularly in the upwelling region, has decreased at 79%, from 305 mm to 65 mm (Fig 4.22b).

During boreal winter (DJF), weak precipitation anomalies are observed with slight drying along the Gulf of Guinea and marginal wetting in southern Nigeria and Cameroon. Surface air temperature anomalies range from $+0.25^\circ\text{C}$ to $+0.75^\circ\text{C}$, with moderate warming concentrated over inland regions, particularly the Sahel. This suggests that even during the dry season, extreme MHWs can induce localized coastal drying and widespread warming over land, likely via thermodynamic feedbacks.

In spring transition season (MAM), precipitation responses are mixed. Drying dominates southeastern West Africa, while localized wet anomalies appear near the western coast. Temperature anomalies are strongest in eastern and central inland areas, with values up to

+0.75°C. These patterns may indicate a delayed monsoon onset or disrupted transitional rainfall due to weakened pre-monsoonal convection possibly linked to altered SST gradients from MHWs.

The JJA season, representing the WAM core, shows pronounced drying across the Guinea Coast and central West Africa, with some wetter anomalies over Nigeria and Cameroon. This is accompanied by widespread surface warming, especially in areas of reduced rainfall, suggesting a suppression of moist convection via land-atmosphere feedbacks. The co-location of warming and drying points to dry-warm feedback mechanisms, reduced cloud cover increases solar heating, enhancing atmospheric stability and weakening monsoonal inflow.

These results align with modeling studies (e.g., Gaetani *et al.*, 2017) showing that SST warming can reduce monsoon rainfall by flattening meridional temperature gradients. MHW-induced anomalies may act as transient analogs of such structural changes expected under long-term climate change.

During SON, the post-monsoon season, positive precipitation anomalies dominate (e.g., over Guinea, Sierra Leone), alongside modest and spatially inconsistent warming. This wetting may reflect delayed retreat of the monsoon and increased instability due to residual oceanic warming. The season's sensitivity to MHWs could be tied to thermodynamic destabilization and enhanced moisture recycling following the monsoon peak.

The seasonal patterns described above underscore the ability of MHWs to modulate the WAM via both thermodynamic and dynamic pathways. MHW-induced warming reduces surface pressure, alters boundary-layer depth, and enhances atmospheric stability, especially over land. The co-occurrence of warming and drying is consistent with reduced moist convection and enhanced subsidence (Duchez *et al.*, 2016; Weller *et al.*, 2019). MHWs also disrupt SST gradients that help drive the seasonal migration of the ITCZ and the northward monsoon flow.

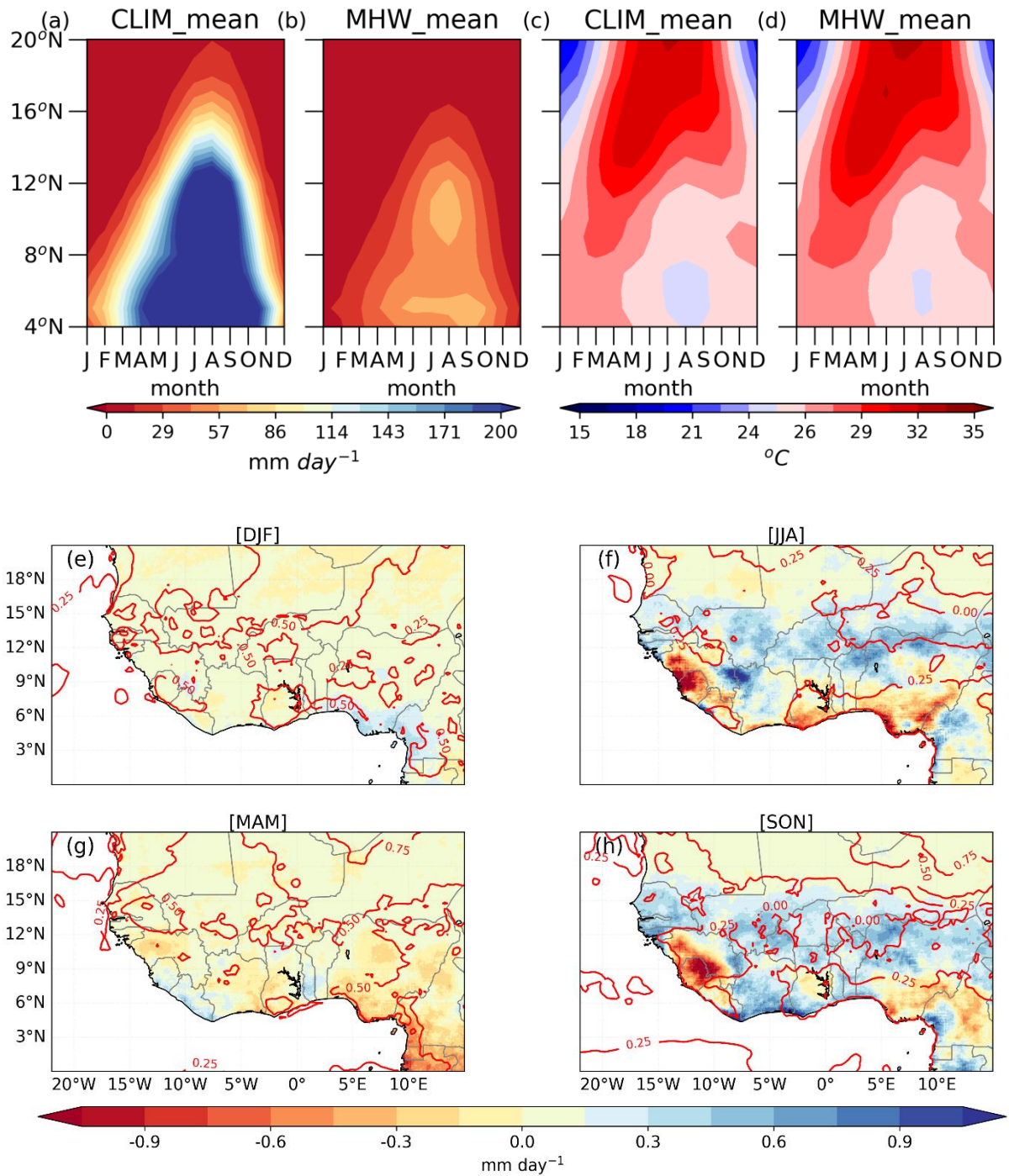


Figure 4.22: Climatology and composite analysis precipitation and surface air temperature during extreme MHW episodes along West African coasts.

These changes can delay or weaken monsoon onset and alter moisture transport, particularly during MAM and SON (Zhang *et al.*, 2019). Notably, during SON, the persistence of warming despite enhanced rainfall may reflect latent heat release and residual moisture availability, as well as thermodynamic destabilization following monsoon withdrawal.

Beyond seasonal averages, MHWs may also modulate intra-seasonal monsoon behavior, including the timing and structure of its onset and active phases. The pre-onset and onset phases of the WAM, characterized by alternating wet and dry spells (Sultan and Janicot, 2003a, b), are highly sensitive to SST anomalies in the tropical Atlantic, especially the Gulf of Guinea. MHWs occurring in DJF and MAM may delay the northward migration of the rainband by weakening land-ocean thermal contrasts and altering lower-tropospheric humidity and pressure gradients. In SON, enhanced rainfall despite warming suggests delayed monsoon retreat or enhanced instability, potentially driven by persistent SST anomalies (Okumura and Xie, 2004; 2006; Parker *et al.*, 2017). These disruptions reflect broader reorganizations in monsoonal circulation, including shifts in surface wind regimes and mesoscale convection, which are not solely attributable to latitudinal movement of the ITCZ.

These findings demonstrate that extreme MHWs can influence the timing, structure, and intensity of the West African monsoon through both large-scale and regional feedbacks. The resemblance between observed MHW-related anomalies and modeled responses to SST warming (Gaetani *et al.*, 2017) suggests that MHWs may serve as short-term analogs of long-term climate change. Understanding these mechanisms is vital for: the seasonal forecasting, especially during transition periods (MAM, SON) and monsoon peak (JJA), agricultural and water resource planning, in regions where rainfall timing is critical, disaster risk reduction, considering the potential for altered hydroclimatic extremes under future warming scenarios.

Partial Summary

This section focused on the potential impact of MHWs on primary productivity in the Northwest African coastal upwelling system. Our results show contrasting trends in chlorophyll a concentration as a function of MHW intensity, with moderate MHW regions showing increases, while strong MHW regions show significant decreases.

The observed non-linear response of chlorophyll-a concentrations to MHW intensity highlights the importance of understanding the severity and duration of heat waves. Moderate MHWs can promote transient increases in productivity, likely due to temporary warming and nutrient availability. In contrast, strong MHWs lead to nutrient limitation, thermal stress, and suppressed primary production, consistent with the hierarchical framework proposed by Hobday *et al.*, (2016), which emphasizes that ecosystem impacts systematically intensify with MHW severity. Our results are consistent with several recent studies.

The moderate MHWs can cause ecosystem stress without catastrophic effects, while strong MHWs often cause mortality and biodiversity loss (Smale *et al.*, 2019). The moderate MHWs can also allow for partial ecological recovery, whereas strong MHWs cause persistent nutrient depletion (Pastor and Khodayar, 2023). The moderate thermal anomalies can stimulate biological activity, but intense, prolonged MHWs reduce vertical nutrient flux and marine productivity (Benthuisen *et al.*, 2020; Oh *et al.*, 2023).

The particular vulnerability of coastal upwelling systems under strong MHW conditions, and the potential for near-permanent MHW states under future climate scenarios (Simon *et al.*, 2023; Oliver *et al.*, 2019). Studies (Rosselló *et al.*, 2023; Martínez *et al.*, 2023) also emphasized the importance of considering spatial variability and methodological definitions when assessing MHW impacts. These results confirm that biological responses to MHW are highly dependent on intensity, duration, and regional characteristics.

The Northwest African upwelling system is particularly vulnerable due to its dependence on vertical nutrient fluxes, which are disrupted during strong MHW conditions. Several studies provide context. MHW intensification was linked to changes in ocean circulation and atmospheric conditions (Xu *et al.*, 2022; Holbrook *et al.*, 2019), not just surface warming trends.

The role of mesoscale eddies in trapping heat was also noted (Bian *et al.*, 2023). This mechanism likely relevant to our study area. The biological effects of MHWs often persist beyond the event itself, leading to long-term ecosystem changes (Frölicher and Laufkötter, 2018; Belkin and Short, 2023). In addition, upwelling dynamics can either buffer or exacerbate the impacts of MHWs (Varela *et al.*, 2021). These authors emphasized that upwelling can mitigate the effects of heat waves when it is sufficiently strong, supporting our finding of increased chlorophyll-a under moderate MHWs. However, when upwelling is weak or overwhelmed by thermal anomalies, as in strong MHW regions, productivity decreases. In addition, the influence of large-scale climate drivers (e.g., ENSO, PDO, IOD) (Dalsin *et al.*, 2023; Kumar *et al.*, 2023), suggests that both global and regional climate variability must be considered when assessing future risks to the Northwest African upwelling.

The vulnerability of upwelling ecosystems extends beyond declines in productivity. Shifts in predator distributions (Welch *et al.*, 2023), disruptions in spawning and recruitment (Shanks *et al.*, 2019), and reduced fishery yields (Cheung and Frölicher, 2020) are predictable consequences of MHW-induced ecosystem changes. Thermal stress effects on species metabolic processes and reproduction (Smith *et al.*, 2023) could further alter community structure and ecosystem services in the region. Our results are consistent with the broader synthesis (Poloczanska *et al.*, 2013; Oliver *et al.*, 2020), which confirms that MHWs are becoming more frequent and intense, especially in vulnerable systems such as coastal upwelling zones.

4.3 Capacity of CMIP5 and CMIP6 Model Outputs in Simulating Northwest African and Gulf of Guinea Coastal Upwelling Systems

4.3.1 Uncertainties in Observational Data

We start this section by analyzing the observational uncertainties over different primary data of SST and wind used for the model evaluations. For the SST, the OSTIA observations were used as the reference SST to assess other primary observation and reanalysis datasets. For the wind components, the ERA5 data were considered as a reference wind to evaluate biases in other observations and reanalyses. These two references data were selected based on their high-resolution and accurate representation of upwelling imprints. Before choosing these datasets, we computed and represented the climatological annual cycle of each dataset. The statistical t-test applied directly on biases to indicate whether these biases are statistically different from zero.

The result of Fig.4.23 indicates that biases between OSTIA and other observation and reanalysis data are systematic and significant in time and space. Almost all the primary observations of SST were slightly superior ($+0.4^{\circ}\text{C}$) to satellite observations (OSTIA) in the North-West African coastal upwelling regions. Both Observations and reanalyses datasets have shown significant warm biases in the Senegal-Mauritania and Gulf of Guinea upwelling regions (in black boxes), except ERSST, where significant cold biases were observed in the northern part of the SMUS. The statistical t-test result indicates that, the difference between OSTIA and other other primary data is pronounced in atmospheric reanalyses (Fig 4.23e, g, h) than observations (Fig 4.23a, b, c) and ocean reanalyses (Fig 4.23d). However, NCEP dataset shows a slightly different (Fig 4.23f). This data is closer to observations, while ERSST (Fig 4.23b) show cold biases in the northern part of SMUS. No significant warm biases were observed in the COBE sets (Fig 4.23c). However, Almost the primary datasets show significant warm biases in the southern part of the SMUS and GGUS, except HadISST. These constant biases could be linked to the regular perturbations of the ITCZ motions drives by West Africa monsoon system.

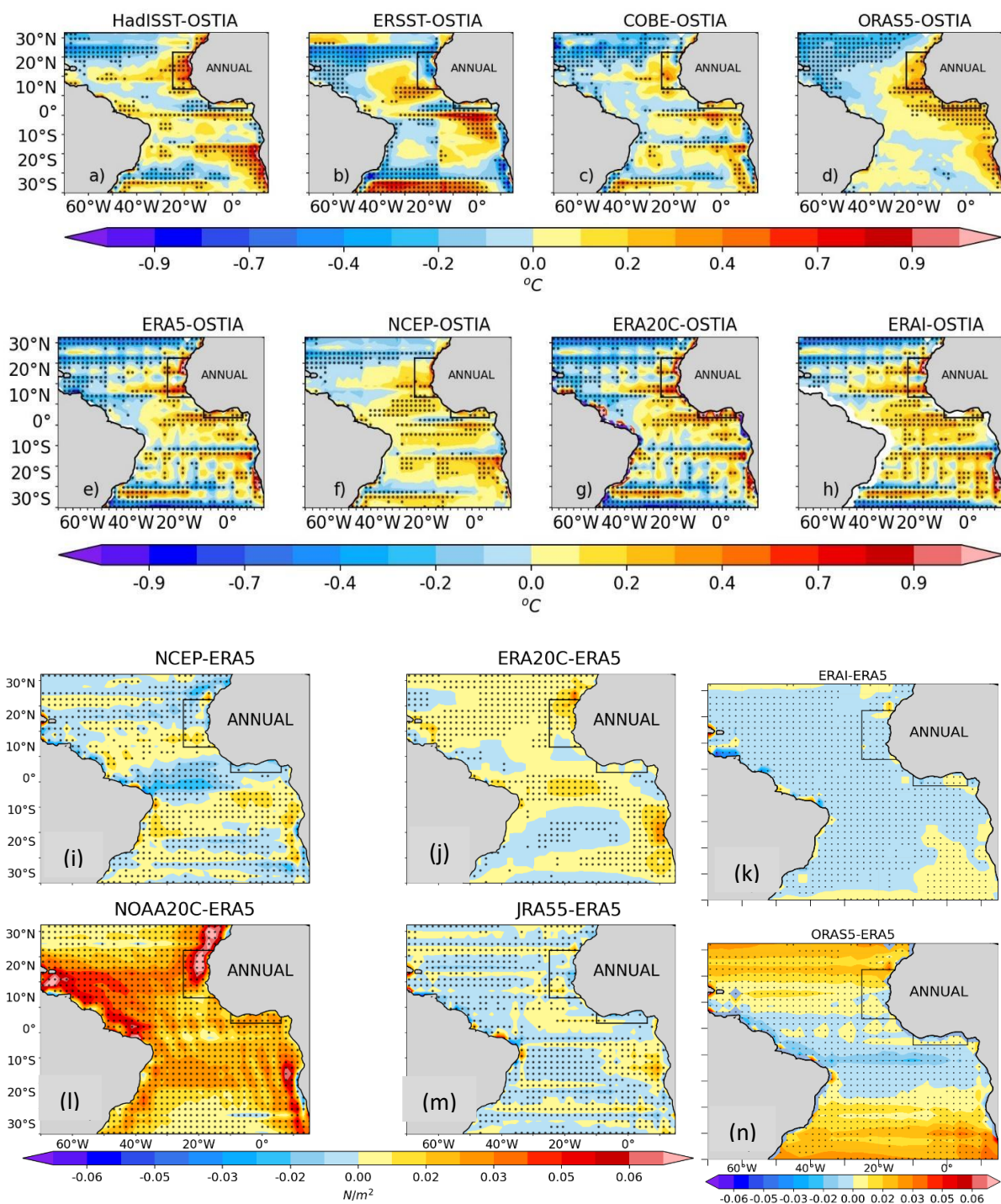


Figure 4.24: Uncertainties in observational SST (a-h) and wind stress (i-n) based on reference OSTIA and ERA5 datasets at 95% interval of confidence.

HadISST show significant biases over the whole SMUS (Fig 4.23a), These important biases could be linked to their lower-resolution compared to OSTIA data. ERA20C SST is weaker than other atmospheric reanalyses due maybe to its limited set of observations and a simpler assimilation approach, which linked mainly on surface pressure and fewer marine observations. In contrast of modern reanalysis like ERA5, which assimilate satellite-derived SST data, ERA20C has lower spatial resolution (1°) and simplified physics, affecting its ability to capture fine-scale SST features and dynamical processes, especially in coastal and upwelling regions. These limitations also introduce biases in long-term variability patterns, making ERA20C less reliable for detailed SST analysis in areas with significant ocean-atmosphere interactions, such as upwelling regions where SST variability is crucial. Thereby, biases in primary observations are almost weak (between -0.5 to 0.5°) in the Northwest African coasts. This encouraged us to use the observational mean of difference SST dataset to evaluate model outputs.

The biases observed in primary wind stress used for the model evaluations are quite different from dataset to another, but almost close to zero except in NOAA20C. The significant positive biases were observed in ERA20C, NOAA20C and ORAS5 data (Fig.4.23 j, l, n), while significant negative biases were included NCEP, ERAI and JRA55 sets (Fig.4.23i, k, m). The positive biases are pronounced in the NOAA20C while the negative biases are pronounced in the ERAI. The positive biases were observed in the whole Tropical Atlantic (Fig.4.23l), and in particular in northern part of SMUS, around the equator (Fig.23j, m), and the southerlies and northerlies frontal zone (Fig.4.23i).

The statistical t-test shows significant biases in ERAI, NOAA20C and ORAS5 than NCEP, ERA20C and JRA-55 data but values close to zero. The higher-biases observed in NOAA20C could overestimated upwelling wind or not capture the local patterns well compared to other

data sources. To avoid the impact of the single observations, we used the observational mean to evaluate model results.

To analyse biases in all the models from 1980 to 2005, a combination of observation (HadISST, ERSST and COBE) SST was judiciously used, integrating ORAS5 data to check the consistency of the observation and reanalysis data with the results of the CMIP5 and CMIP6 climate models. Also, the ensemble means of atmospheric reanalysis (ERA-Interim, ERA5, NOAA20C, ERA20C, NCEP, JRA-55) or ocean reanalysis (ORAS5) were used to analyse model winds, in order to minimize the single observation bias. The model results were evaluated against this observational uncertainty.

4.3.2 Simulating SST Patterns Along Northwest African and Gulf of Guinea Coasts

Here, we focus on the annual-mean SST stratification averaged along each upwelling coast, as the annual-mean changes are similar to upwelling-season mean changes. Like the winds, the SST again show differences between the CMIP5 and CMIP6.

The spatial and temporal distribution of SST over the ocean's surface are critical for understanding ocean-atmosphere interactions, climate variability, and ecosystem dynamics. In this section, the ability of CMIP5 and CMIP6 models to capture the observed SST patterns over the Senegalo-Mauritanian and Gulf of Guinea coastal upwelling areas (SMUS and GGUS) was conducted using the annual mean state and standard deviation of the multi-model means (MMM) calculated from each generation of climate models. As mentioned in the previous section, the MMM and standard deviations for CMIP5 and CMIP6 were derived by averaging the individual model means obtained with different members. We analyzed model capacities to capture the annual mean state and variability of SST in the whole Tropical Atlantic where the two upwelling systems are located, and during the upwelling periods in each upwelling region when cooler SSTs due to nutrient-rich cold water rising to the surface are vital for marine ecosystems and fisheries.

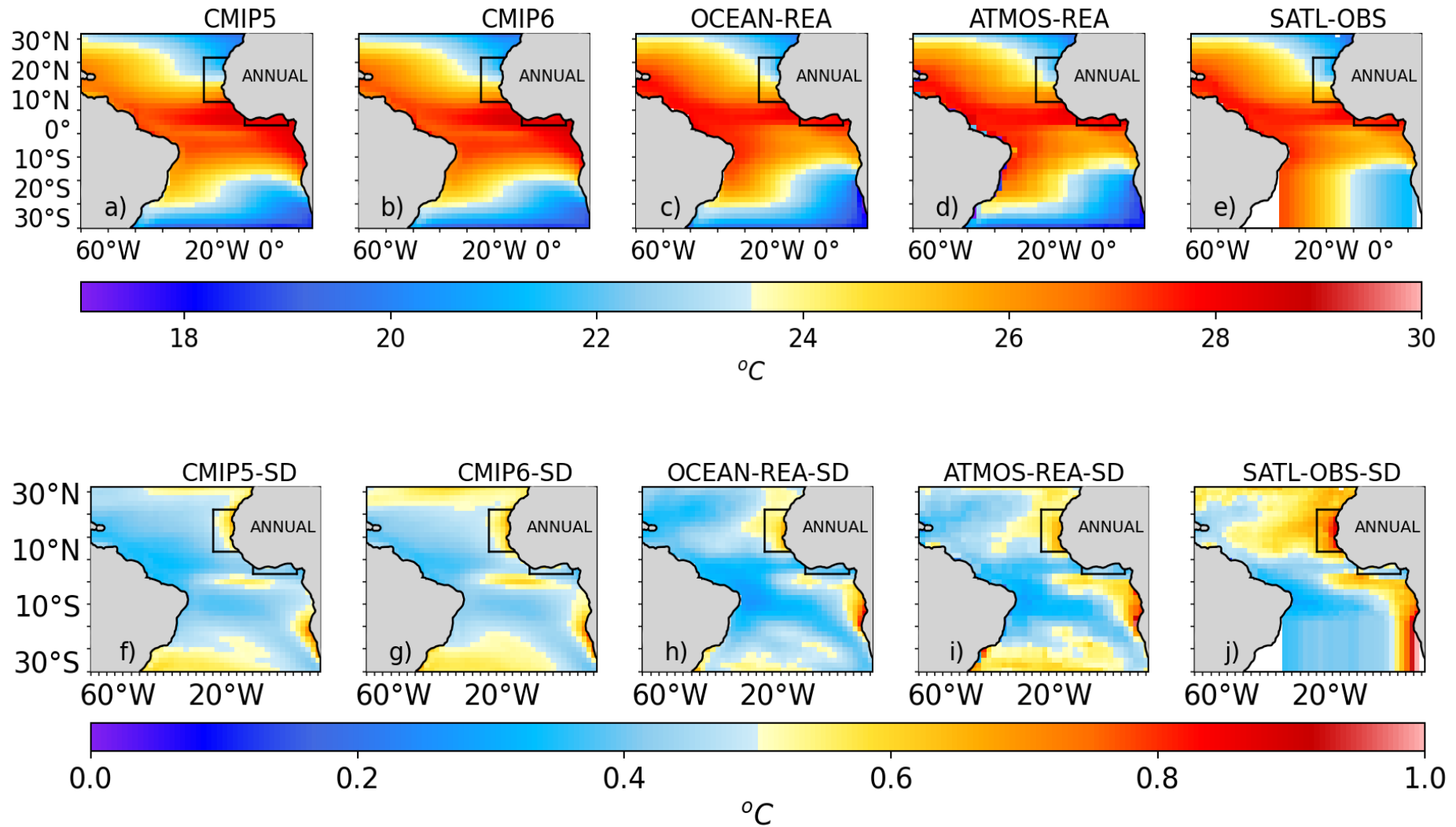


Figure 4.24: Annual mean state and standard deviation of SST in observations (ocean and atmospheric reanalyses and satellite observations) (a-e), and CMIP5 and CMIP6 multi-model means (f-j).

The results of Fig. 4.24 show that the MMMs of both CMIP5 and CMIP6 generations (Fig. 4.24a, b) generally simulate the annual mean state of SST in the tropical Atlantic (33°S-33°N) well, but with a slight overestimation of approximately +1°C compared to observational and reanalysis data (Fig. 4.24c, d, e). In the southern SMUS region (14°N-10°N) and the GGUS, MMM results reveal significant warm biases in most models. However, no substantial improvement is observed between CMIP5 and CMIP6 (Fig. 4.24a, b) MMM in capturing the annual mean state of SST. Regarding variability, the models' standard deviations (Fig. 4.24f, g) broadly align with primary data (Fig. 4.24h, i, j) in the equatorial Atlantic, with slight improvements in CMIP6 (Fig. 4.24g). Nonetheless, variability observed in satellite data (OSTIA) remains poorly simulated (Fig. 4.24j).

In the Northwest Africa coastal upwelling regions, model simulations during upwelling periods (winter-spring and summer) indicate that CMIP6 (Fig. 4.25b, g) captures alongshore SST patterns slightly better than CMIP5 (Fig. 4.25a, f), particularly in the southern SMUS (14°N-10°N). Additionally, in the GGUS (Fig. 4.26), CMIP6 (Fig. 4.26b, g) captures spatial SST variability more effectively, although persistent warm biases are still observed, especially during summer (Fig. 4.26a, b). The high mean state and variability of SST are still visible on the Gulf of Guinea coasts, especially in the western part of GGUS.

The improvements in CMIP6 MMM in simulating SST patterns are partly attributed to the increased number of participating models and enhanced capacity to simulate coastal and mesoscale processes. Despite these advancements, models still struggle to capture SST variability observed in satellite data (Figs. 4.24j, 4.25j and 4.26j).

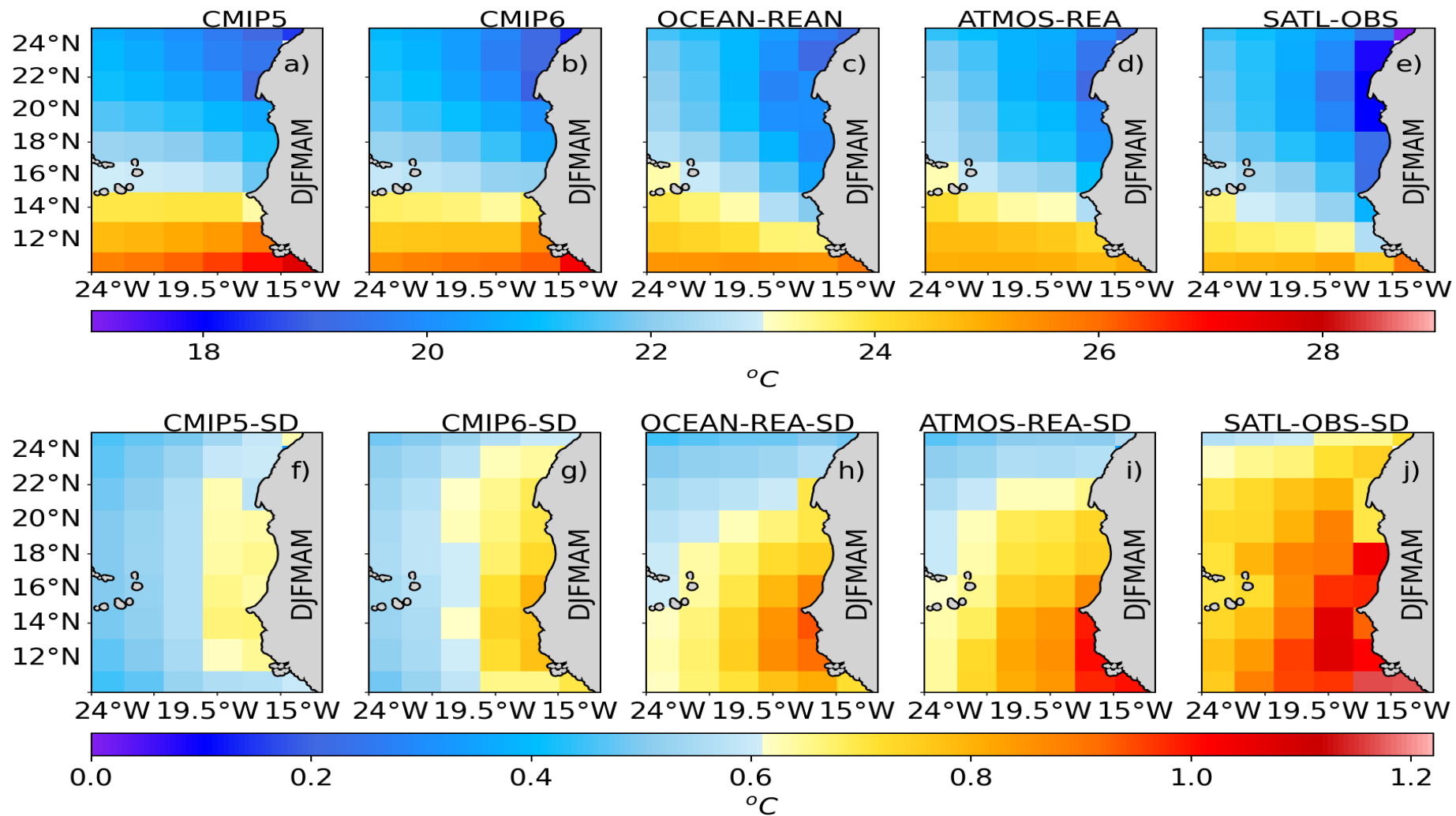


Figure 4.25: Performances of CMIP5 and CMIP6 models in simulating observed SST in the Senegal-Mauritania coastal upwelling system (SMUS) computed during the winter-spring (December-May).

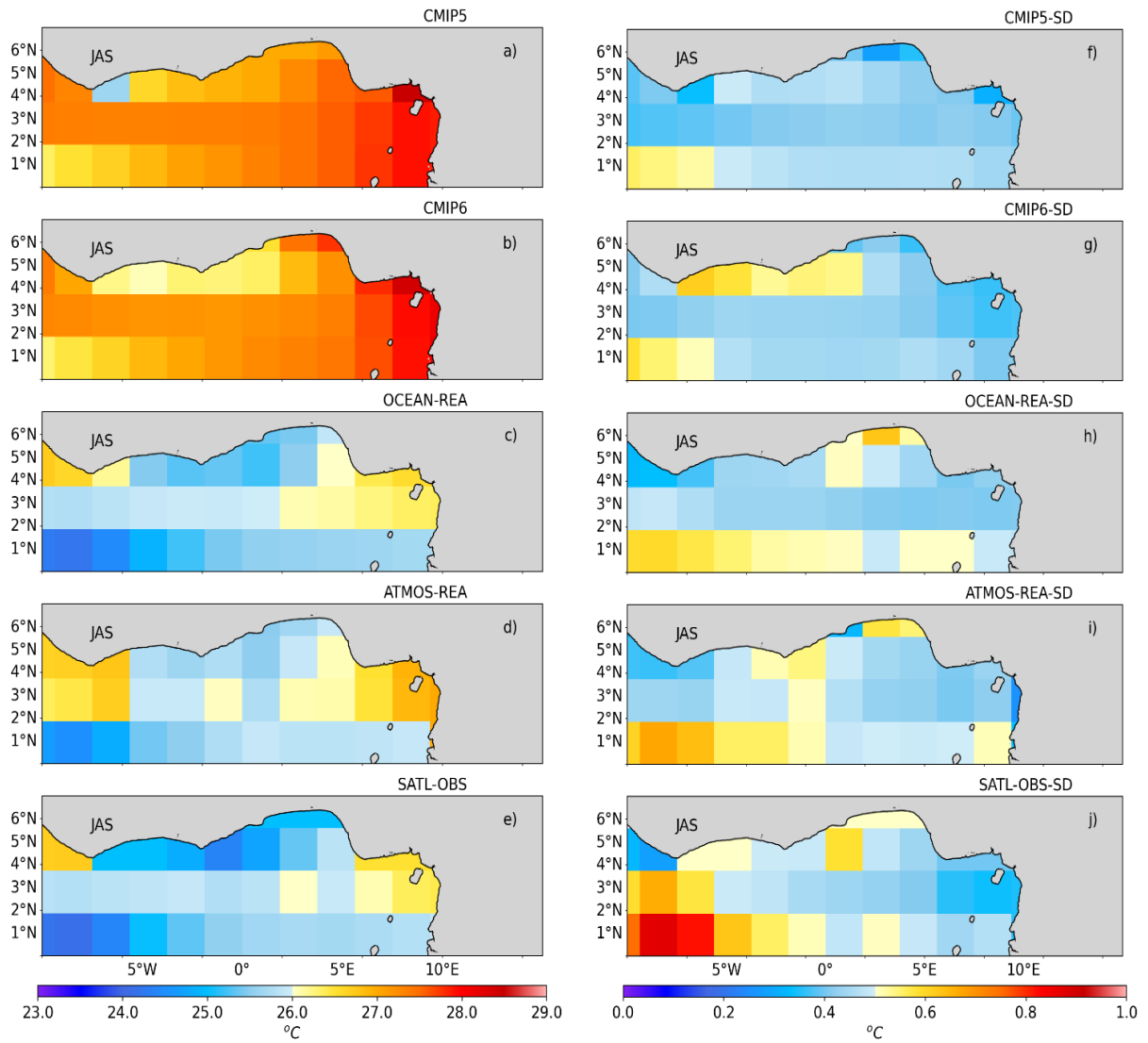


Figure 4.26: Performances of CMIP5 and CMIP6 models in simulating observed SST in the Gulf of Guinea coastal upwelling system (GGUS) computed during the winter-spring (July-September).

The annual SST cycles (Fig. 4.27) indicate that CMIP6 MMM (curve oranges) aligns more closely with oceanic reanalysis (curve blues) and satellite observations (curve green), while CMIP5 MMM (curve reds) better matches atmospheric reanalysis data (curve blacks). In the Tropical Atlantic as in the SMUS (Fig. 4.27a, b), the two generations of climate models capture the observed annual cycle of SST. The minima and maxima peak are well represented in both two generations of climate models. CMIP6 has simulated SST well during the non-upwelling period (June-December), where the MMM (orange curve) accurately captured satellite observations (green) signal (Fig.4.27b). However, challenges remain. Models struggle to capture well SST during the winter-spring in the SMUS, and overestimate SST from January to May.

In the GGUS, the annual cycle of SST is not captured well by the two generations of climate models. Simulated cycles are shifted by one month for both minimum and maximum peaks compared to observations. The minima peaks observed in August (Fig. 4.27c), were simulated in September, while the maxima peaks observed in April were simulated in March. Moreover, the MMM show that the two generations of model overestimate (higher SSTs) SST during upwelling periods ($+0.3^{\circ}\text{C}$) and underestimate it (lower SST) during non-upwelling periods (-0.5°C). The comparison between CMIP5 and CMIP6 signals clearly shows systematic difference around $+2.5^{\circ}\text{C}$ in the Tropical Atlantic and the two upwelling regions. This indicates that CMIP6 MMM have improved in simulating high SST in the tropical Atlantic and lower SST in the upwelling. However, these improvements are not observed over all models, as those from GISS. Model biases were analyzed against observational mean and uncertainty. Thus, we analyzed each single model mean from each generation of CMIP against the observational mean, then averaged them to have the MMM biases. However, the model sign agreement calculated between each single model mean and the MMM, was used to show the areas that models agree substantial warm or cold biases.

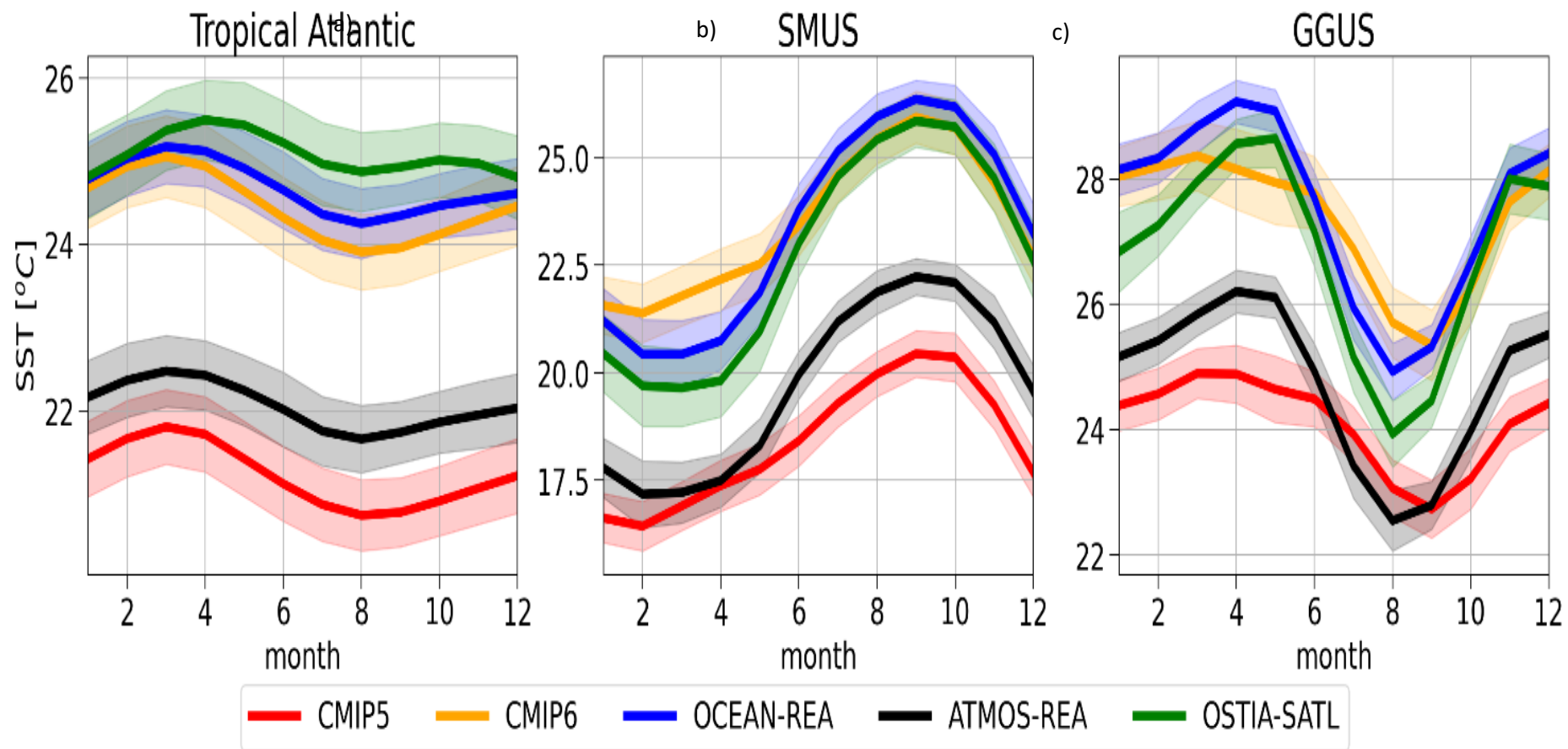


Figure 4.27: Capacity of CMIP5 and CMIP6 models in simulating the seasonal the observed SST in the Tropical Atlantic (a), Senegal-Mauritania (b) and Gulf of Guinea (c) upwelling systems.

The result presented by Fig. 4.24 shows that warm biases in West African coasts remain significant in both generations of climate models but are reduced in CMIP6 compared to CMIP5 (from $+2.5^{\circ}\text{C}$ to $\leq 1^{\circ}\text{C}$ in SMUS and from $+2^{\circ}\text{C}$ to $\leq 1.5^{\circ}\text{C}$ in GGUS). The biases observed in the West African coast, particularly in SMUS and GGUS, may be linked to inadequate representation of coastal river runoff and local upwelling processes, which are challenging to simulate. These limitations are especially pronounced in certain models, such as those from GISS, where significant warm biases persist. The further analysis reveals that CMIP5 and CMIP6 models exhibit substantial cold biases in the alongshore SST and in the northern SMUS where upwelling is almost permanent and warm biases in the Gulf of Guinea (Fig. 4.29i, j, k, l) as well as the southern part (14°N - 10°N) of SMUS (Fig. 4.29e, f, g, h) where the seasonal upwelling is weak. These evidence biases are more pronounced when compared with ocean reanalysis (Fig. 4.29e, g, i, k) than atmospheric reanalysis (Fig. 4.29f, h, i, l), with CMIP6 showing better agreement with atmospheric data (Fig. 4.29d).

Since SST variability in Northwest African coastal upwellings is largely driven by wind stress, an additional assessment of the models' ability to simulate wind patterns in SMUS and GGUS was conducted.

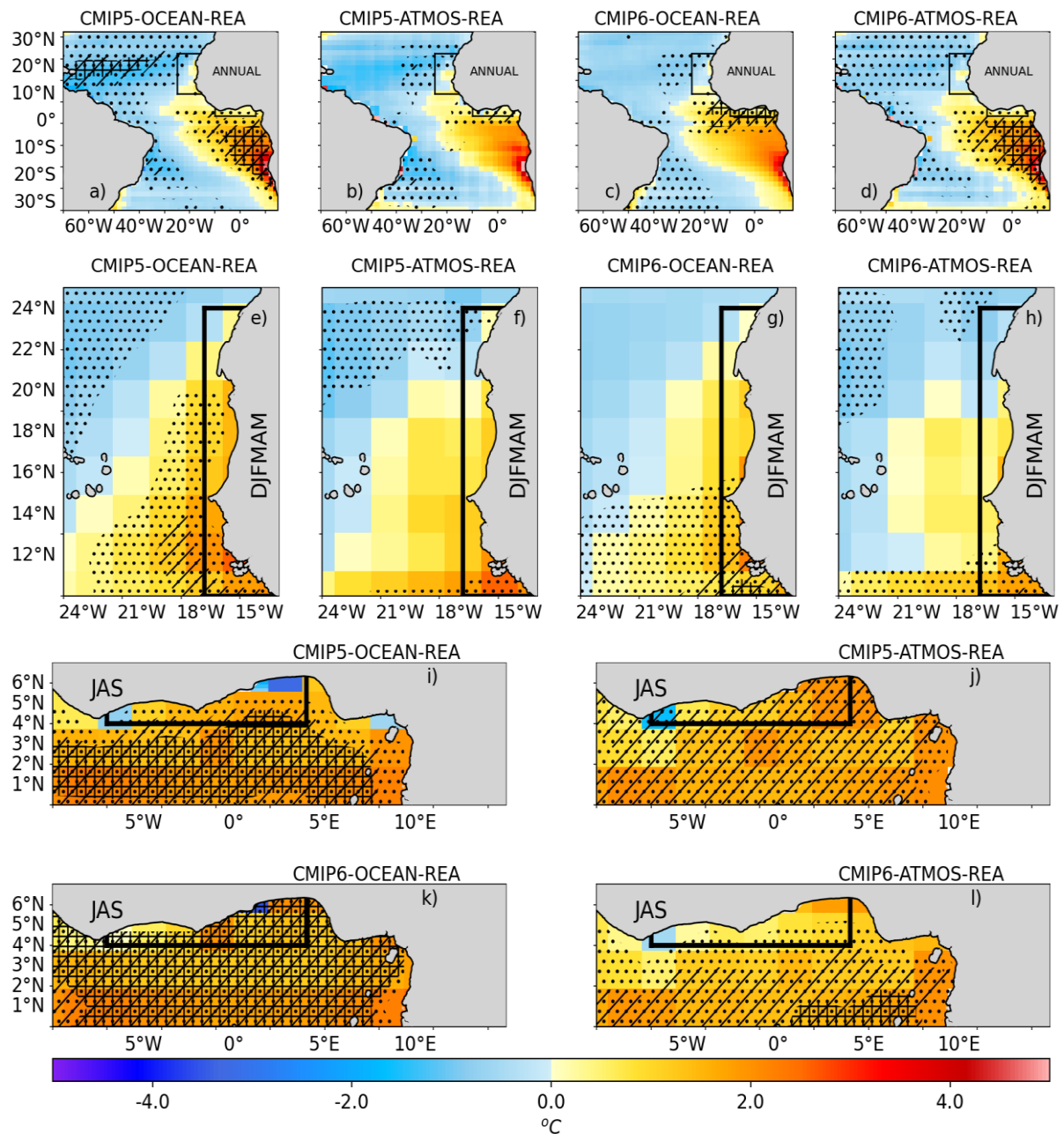


Figure 4.28: CMIP5 and CMIP6 model biases in simulating SST the Tropical Atlantic, Senegal-Mauritania and Gulf of Guinea coastal upwelling systems.

4.3.3 Simulating Wind Patterns Along Northwest African and Gulf of Guinea Coasts

The Northwest African coastal upwelling systems are influenced by the seasonal activity of trade winds, guided by the movement of the ITCZ and shifts in the West African Monsoon (WAM). This section evaluates the ability of CMIP5 and CMIP6 models to simulate the spatial and temporal distribution of surface winds over the SMUS and GGUS regions. Both CMIP5 and CMIP6 multi-model means (MMMs) simulate wind direction well in the whole tropical Atlantic, and in the Northwest African coastal upwelling systems (Fig. 4.29). However, CMIP6 shows slight improvements over CMIP5 in simulating surface wind fields. CMIP6 is closer to the observational mean and exhibits smaller biases in high-wind regions (Fig. 4.29b). Despite these improvements, approximately 45% of CMIP6 models still underestimate annual wind speed.

In SMUS, both CMIP generations accurately reproduce wind speed and direction (Fig. 4.29g, h), with minimal biases ranging from -1 to 1 m/s (Fig. 4.29j, k). However, differences between the two generations (Fig. 4.29i) remain small ($<+0.5$ m/s), indicating no substantial change in CMIP6 MMM. In contrast, models perform poorly in wind fields in the GGUS. Challenges in accurately simulating wind speed persist. Models consistently underestimate wind speed components during the summer upwelling. CMIP5 and CMIP6 fail to capture observed wind speeds accurately (Fig. 4.29m, n), with CMIP6 showing only marginal improvements (Fig. 4.30q). While CMIP6 slightly increases simulated wind speed, bringing it closer to observations, the improvements remain minimal (<0.5 m/s). The model sign agreement indicates that substantial negative biases remain in the equatorial region including Gulf of Guinea coasts and in the northern part of the SMUS.

The comparison between CMIP5 and CMIP6 (Fig. 4.29d, e) shows that CMIP6 is closer to atmospheric reanalysis and simulates a close surface wind field with small biases in the strong

wind regions (Fig. 4.29k), indicating no substantial improvement in the CMIP6 MMM. In the GGUS, climate models (Fig. 4.29n, o) fail to capture observed wind speeds accurately (Fig. 4.30m). Although CMIP6 shows slight improvements in the multi-model mean (Fig. 4.29r), many models still underestimate wind speed components (Fig. 4.29q, r). Bias analysis reveals a small increase in wind speed in CMIP6, bringing it closer to observations, but the improvements remain marginal (<1 m/s).

The analysis of simulated wind speed patterns over the Tropical Atlantic, SMUS, and GGUS reveals some improvements in CMIP6 MMM, particularly from February to July in the tropical Atlantic (Fig. 4.30a) and June to September in SMUS (Fig. 4.30b). Both CMIP generations capture the maximum wind speed peak (July) in the tropical Atlantic with a one-month lag to the observed (August). The similar result was observed with the minimum peak in the SMUS. Models shift one-month lag (September) to the observed minimum in (October), and underestimate wind variability. In the GGUS, the observed annual cycle of wind speed is not well reproduced. While both MMMs capture the maximum peak in August, CMIP6 shows slight improvements (Fig. 4.30c). However, models tend to overestimate wind speed during spring and underestimate it during the summer maximum.

Despite minor improvements observed in CMIP6, biases remain evident in both CMIP generations. Negative biases are particularly prominent in the equatorial region and northern SMUS. While CMIP6 reduces these biases slightly and performs better in high-wind regions, its improvements over CMIP5 are limited.

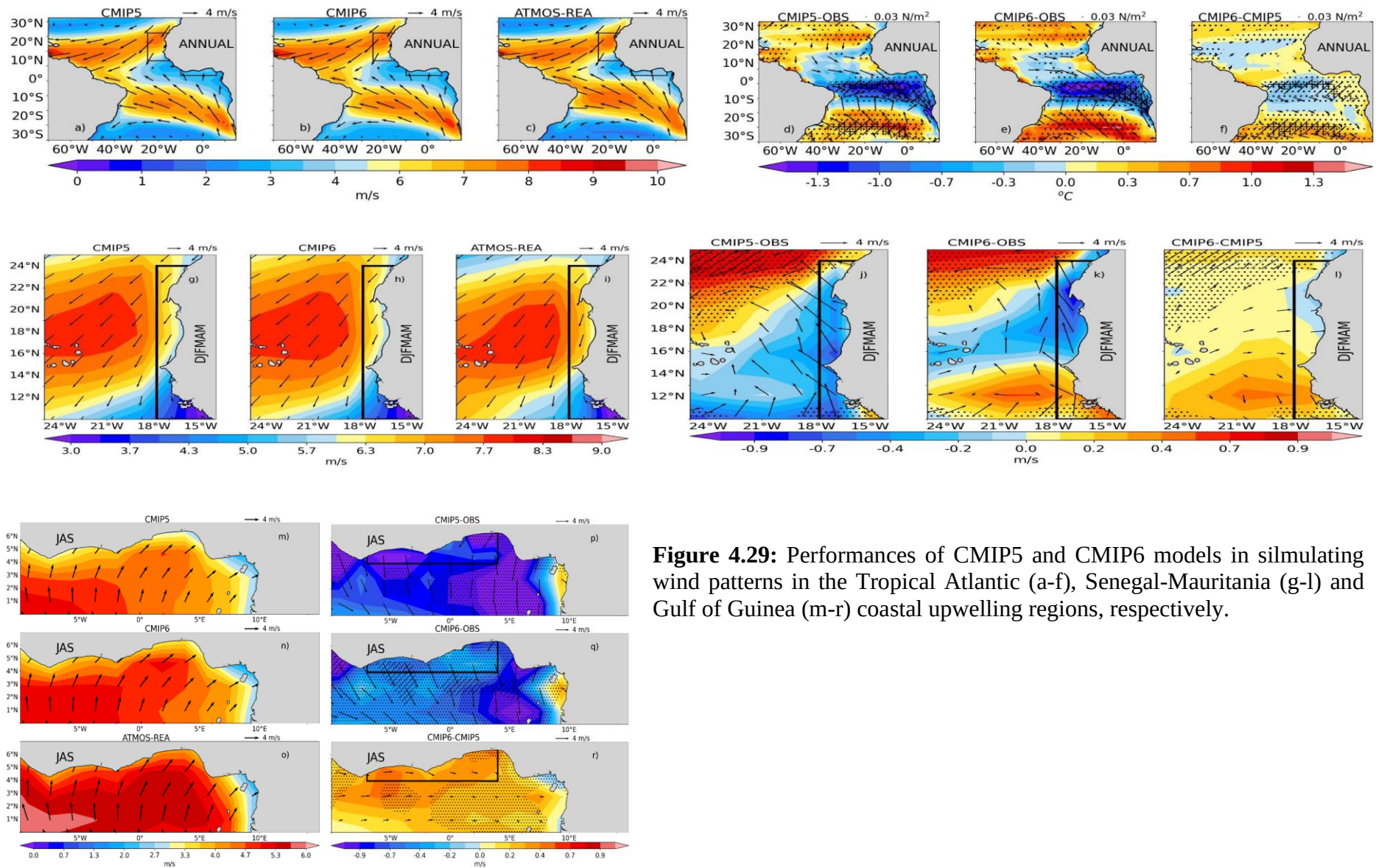


Figure 4.29: Performances of CMIP5 and CMIP6 models in simulating wind patterns in the Tropical Atlantic (a-f), Senegal-Mauritania (g-l) and Gulf of Guinea (m-r) coastal upwelling regions, respectively.

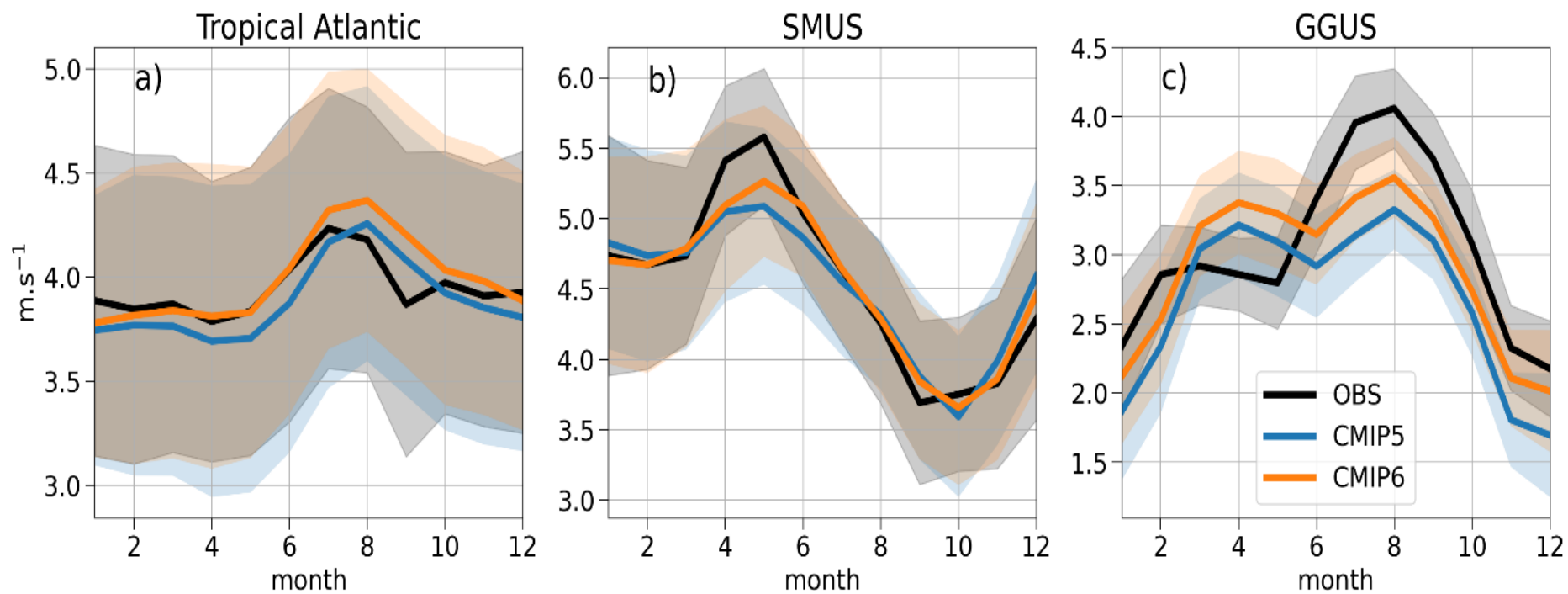


Figure 4.30: Annual cycles of wind speed in the tropical Atlantic (a), Senegal-Mauritania (b) and Gulf of Guinea upwelling systems. Black curves are observations, blue curves are CMIP5 multi-model mean and orange curves are CMIP6 multi-model mean. Shadings are standard deviations.

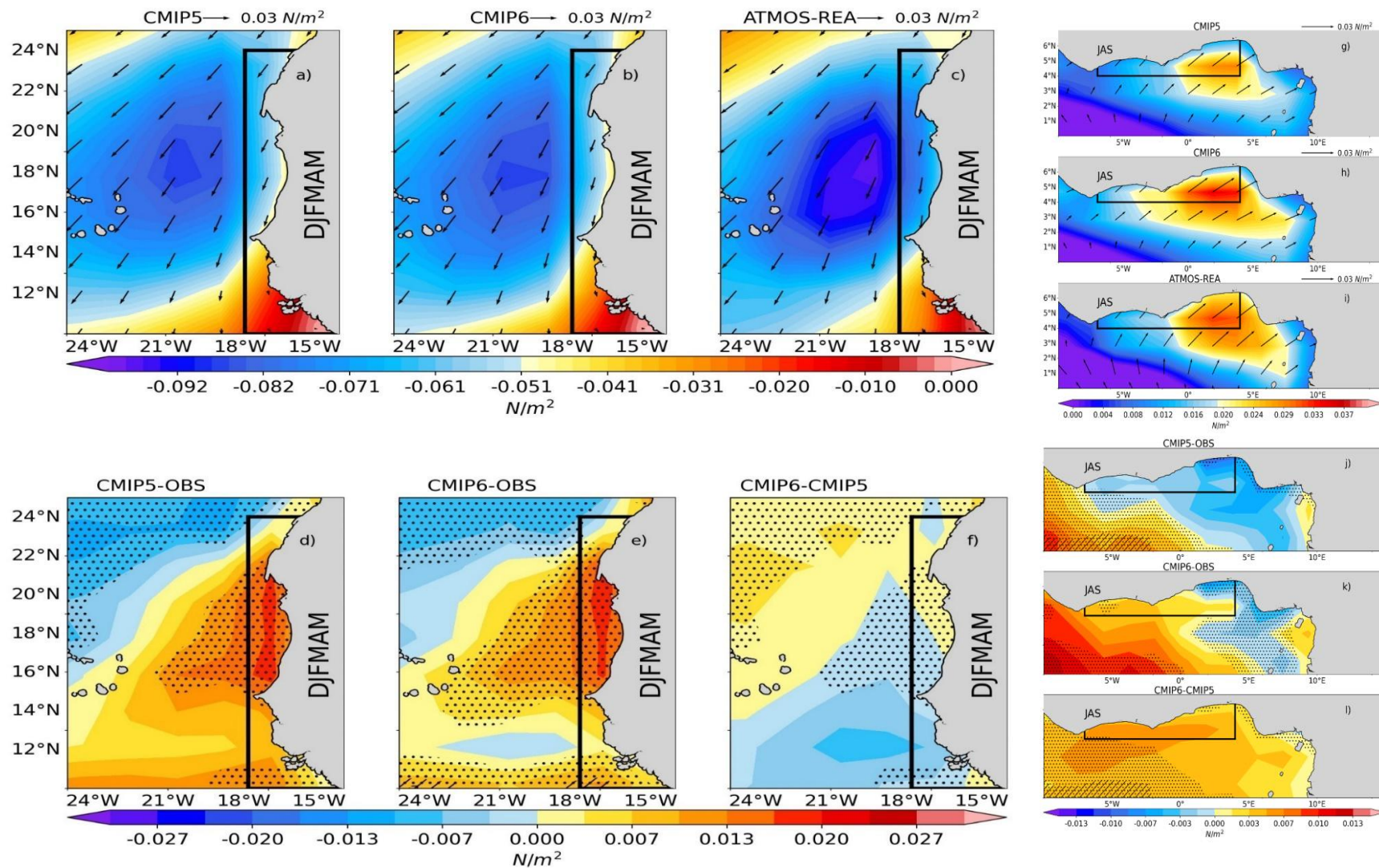


Figure 4.31: Performance of CMIP5 and CMIP6 models in simulating wind stress during winter-spring (December-May) and summer (July-September) in the Senegal-Mauritania and Gulf of Guinea coastal upwelling systems.

The model abilities to capture upwelling-favorable wind stress, were examined during the upwelling the winter-spring in the SMUS and summer in the GGUS (Fig. 4.32). The meridional wind stress that drives the SMUS is well represented in both CMIP5 and CMIP6 models (Fig. 32a, b). However, CMIP6 continues to underestimate the maximum wind stress. Model sign agreement shows a significant positive bias in coastal regions (Fig. 4.32e, f), though there is some improvement in the CMIP6 MMM.

In the GGUS, the zonal upwelling wind stress simulated during the summer period (Fig. 4.32h, i) is less accurately represented by the climate models. Notably, CMIP6 MMM captures the observed spatial maximum wind stress, which CMIP5 MMM underestimated. Analysis of the annual cycle of upwelling-favorable wind stress in the SMUS and GGUS (Fig. 4.32a, b) indicates that CMIP6 MMM reproduces the annual cycle well, although it underestimates the overall strength. CMIP6 models correctly capture the timing of minimum and maximum wind stress periods. In the following, we focus our analyses on the simulated upwelling indices in CMIP6.

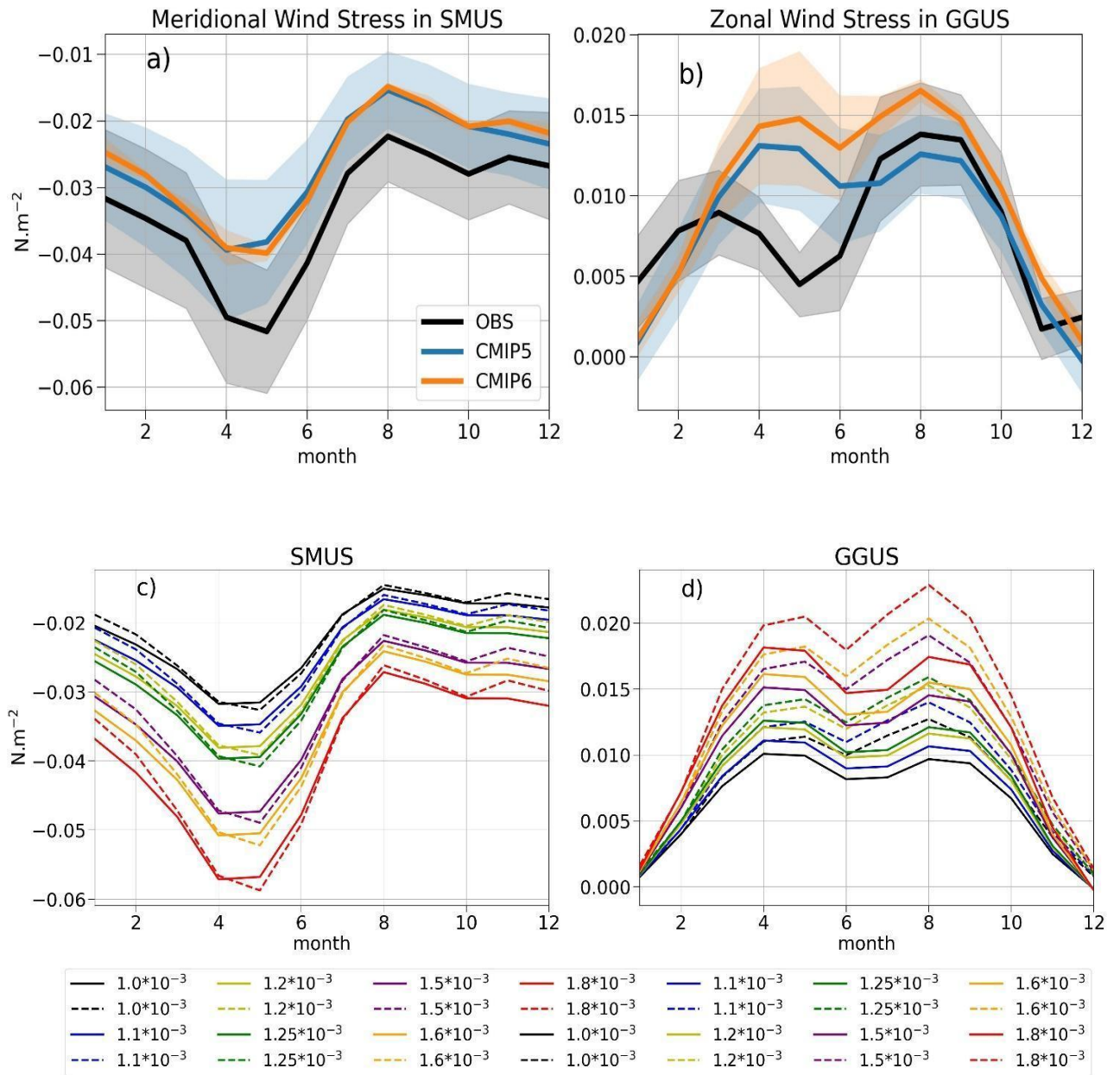


Figure 4.32: Effect of drag coefficient in CMIP5 and CMIP6 models during the annual cycle of wind stress in the Senegal-Mauritania and Gulf of Guinea coastal upwelling syst

4.3.4 Simulating Seasonality of Northwest African and Gulf of Guinea Coastal Upwelling

This section evaluates the ability of CMIP5 and CMIP6 models to simulate the annual cycle of upwelling indices based on wind stress and SST in the SMUS (Figs. 4.33 and 4.35) and GGUS regions (Figs. 4.34 and 4.36), respectively.

4.3.4.1 Wind-driven Coastal Upwelling Indices

Wind-driven coastal upwelling has been evaluated in climate models using the Ekman transport and the wind stress curl-driven. The Ekman transport computed from the upwelling-favorable wind stress and the wind stress curl-driven indicate that both CMIP5 and CMIP6 models reproduce the general annual cycle of wind-driven upwelling in the SMUS but underestimate maximum Ekman transport from April to August (Fig. 4.33b, c). CMIP6 shows slight improvement in spring upwelling wind stress but continues to underestimate Ekman transport during this period. Seasonal biases persist, with underestimation from March to June and overestimation thereafter. The two MMM capture the maximum peak of Ekman upwelling with one-month lag. The maximum peak of Ekman upwelling observed in May (Fig. 4.33a), is weakly simulated in June (Fig. 4.33b, c). No significant improvement was found between the two phases of the CMIP models (Fig. 4.33d, e). Analysis of model biases in simulating the annual cycle of Ekman upwelling shows negative biases from March to June and positive biases after this period in both CMIP phases. It shows that CMIP6 still simulates weak upwelling wind stress during spring and a strong Ekman transport after the spring period.

The analysis of Ekman transport and wind stress curl-driven upwelling in the GGUS (Fig 4.34) reveals critical insights into the strengths and limitations of CMIP5 and CMIP6 climate models in simulating observed patterns. The comparison between CMIP6 and CMIP5 indicates that CMIP6 MMM shows higher Ekman transport and wind stress curl-driven values from February to June compared to CMIP5 (Fig. 4.34f).

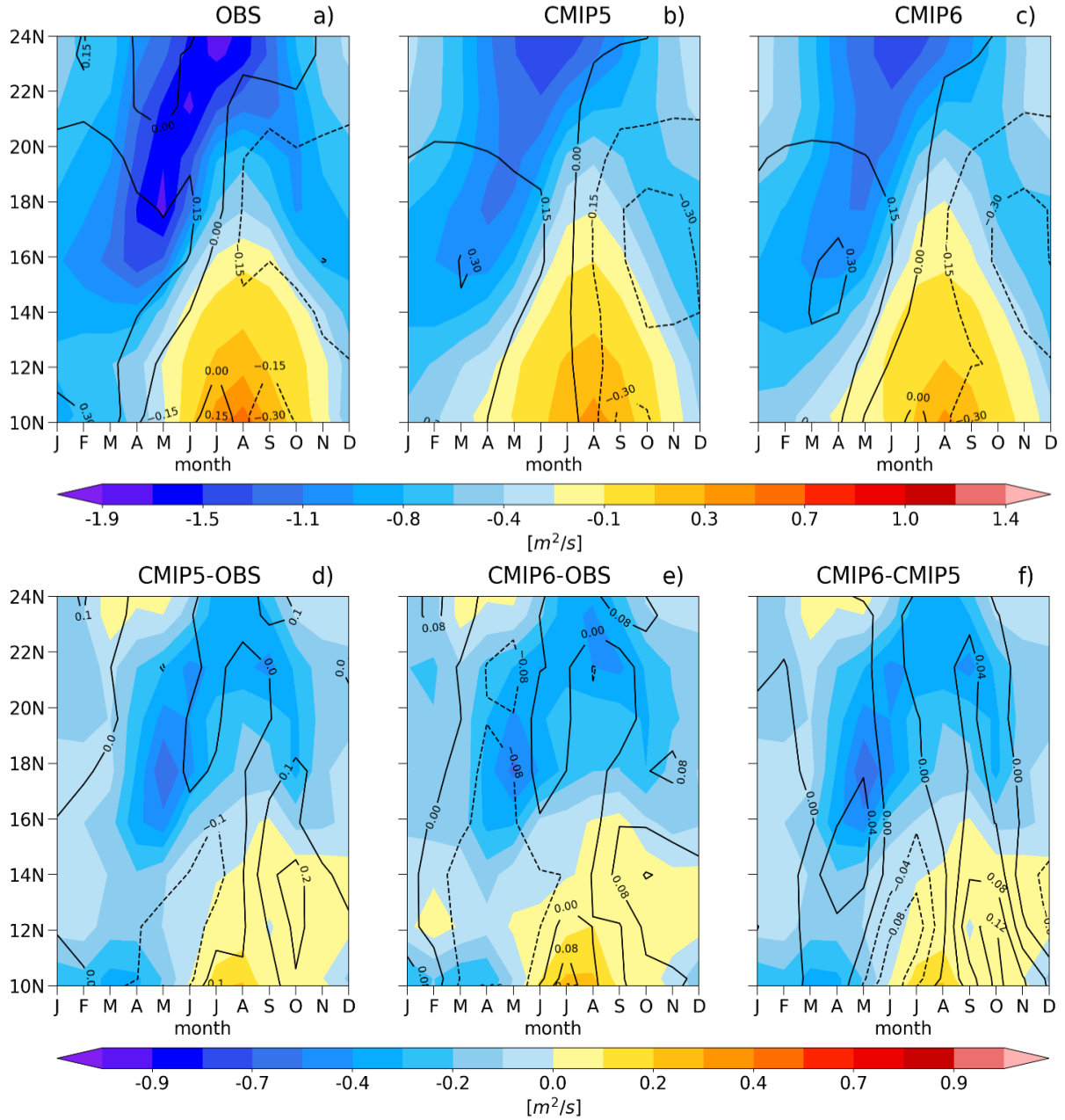


Figure 4.33: Ability of CMIP5 and CMIP6 models in simulating observed wind-driven upwelling (Ekman dynamics) including zonal Ekman transport (color shading) and wind stress curl driven upwelling in $m.day^{-1}$ (contours) in the Senegal-Mauritania coastal upwelling system.

During the upwelling period (July-September), CMIP6 values are lower than CMIP5, though both exceed observed values. While the models capture the general seasonal structure, they

underestimate the variability of Ekman transport. Both CMIP5 and CMIP6 models capture the two maximum peaks of Ekman transport observed in the GGUS over the annual cycle, but fail to accurately simulate observed wind-driven upwelling, particularly the zonal wind stress and meridional Ekman transport driving summer upwelling (Fig 4.34). The models accurately simulate the August peak (Fig. 4.34b, c), which aligns with observed values. Both CMIP generations of climate models overestimate the observed maximum peaks of Ekman transport, particularly in the July–August period. Simulated maximum values ($-1.4 \text{ m}^2/\text{s}$) exceed the observed ($-1.2 \text{ m}^2/\text{s}$).

CMIP6 was improved in simulating Ekman transport from February to May where CMIP5 MMM produced higher-than-observed values. However, the March peak was poorly captured, with models shifting the maximum to May instead (Fig. 4.34b, c). Positive biases ($\sim +0.9 \text{ m}^2/\text{s}$) are evident in both CMIP5 and CMIP6 between February and June, with CMIP6 showing persistent positive biases from February to December. These biases indicate an overestimation of Ekman transport during much of the year. While there is a dynamical consistency between CMIP5 and CMIP6 simulations in the wind-driven upwelling index off the Northwest African coast where wind changes are largely insignificant, future SST-based upwelling index analysis show a more perplexing picture.

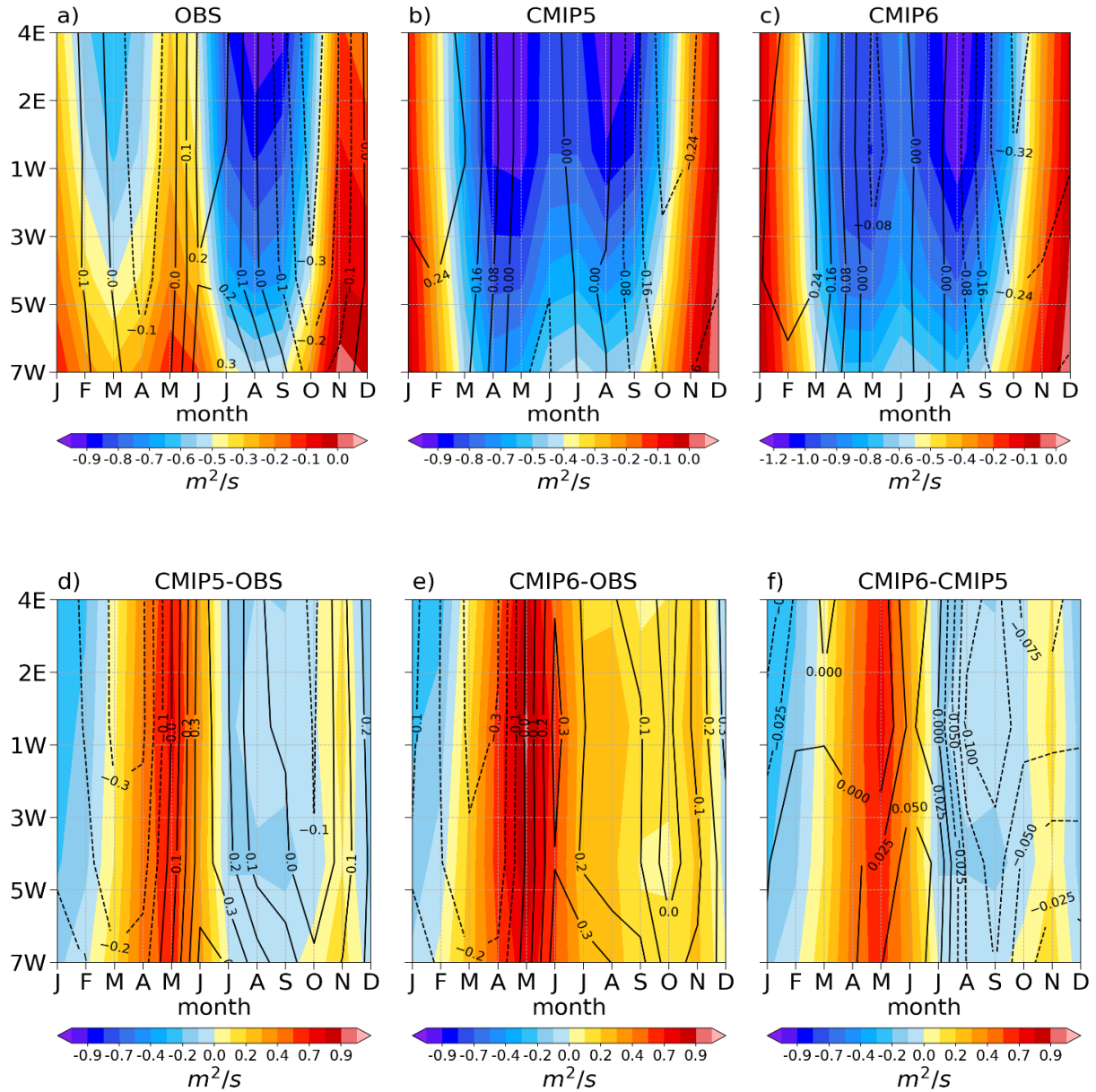


Figure 4.34: Ability of CMIP5 and CMIP6 models in simulating observed wind stress driven upwelling including meridional Ekman transport (colour shading) and wind stress curl driven upwelling (contours) in the Gulf of Guinea coastal upwelling system.

4.3.4.2 SST-based Upwelling Indices

The analysis of SST and upwelling indices in the SMUS (Senegal-Mauritanian Upwelling System) highlights notable improvements in CMIP6 over CMIP5, though biases remain. CMIP models simulate the annual SST cycle with reasonable accuracy particularly north of $14^\circ N$, capturing the seasonal structure effectively (Fig. 4.35b, c). However, in the southern part of $14^\circ N$, both CMIP5 and CMIP6 struggle to simulate observed SST-based upwelling indices,

leading Overestimated SST values and underestimated upwelling indices, especially during May-December.

CMIP6 models show significant improvement in reducing SST biases, particularly in the southern upwelling region (Fig 4.35d, e). SST biases are reduced by up to 1°C compared to CMIP5 (Fig 4.35d, e). This leads to improved upwelling indices, though biases persist. From May to December, both CMIP generations continue to underestimate the maximum SST observed during this period and overestimate SST and underestimate the strength of upwelling indices.

CMIP6 shows a slight improvement over CMIP5 in simulating SST-based upwelling indices. The weak upwelling indices of CMIP5 (Fig. 4.35b) are marginally improved in CMIP6 (Fig. 4.35c), bringing them closer to observed values (Fig. 4.35a). The difference map (Fig. 4.35d) indicates a significant increase in upwelling indices in CMIP6, with SST differences up to 1°C compared to CMIP5. Despite improvements, CMIP6 MMM still overestimates SST and underestimates upwelling indices. The reduction of SST biases in CMIP6 does not eliminate all errors. Persistent biases remain in simulating the amplitude of SST variations and the strength of upwelling during the non-seasonal period.

CMIP6 represents a clear step forward in improving the representation of SST and upwelling indices compared to CMIP5, particularly in reducing SST biases and improving upwelling indices south of 14°N. However, persistent challenges in capturing observed patterns, especially during the non-seasonal upwelling period, indicate that further refinements are needed in both generations of climate models. The analysis of SST and upwelling indices in the GGUS (Fig 4.36) reveals that CMIP models capture certain aspects of the system's dynamics but face significant limitations. Both CMIP5 and CMIP6 models (Fig. 4.36b, c) simulate the annual SST cycle but fail to represent its variability adequately.

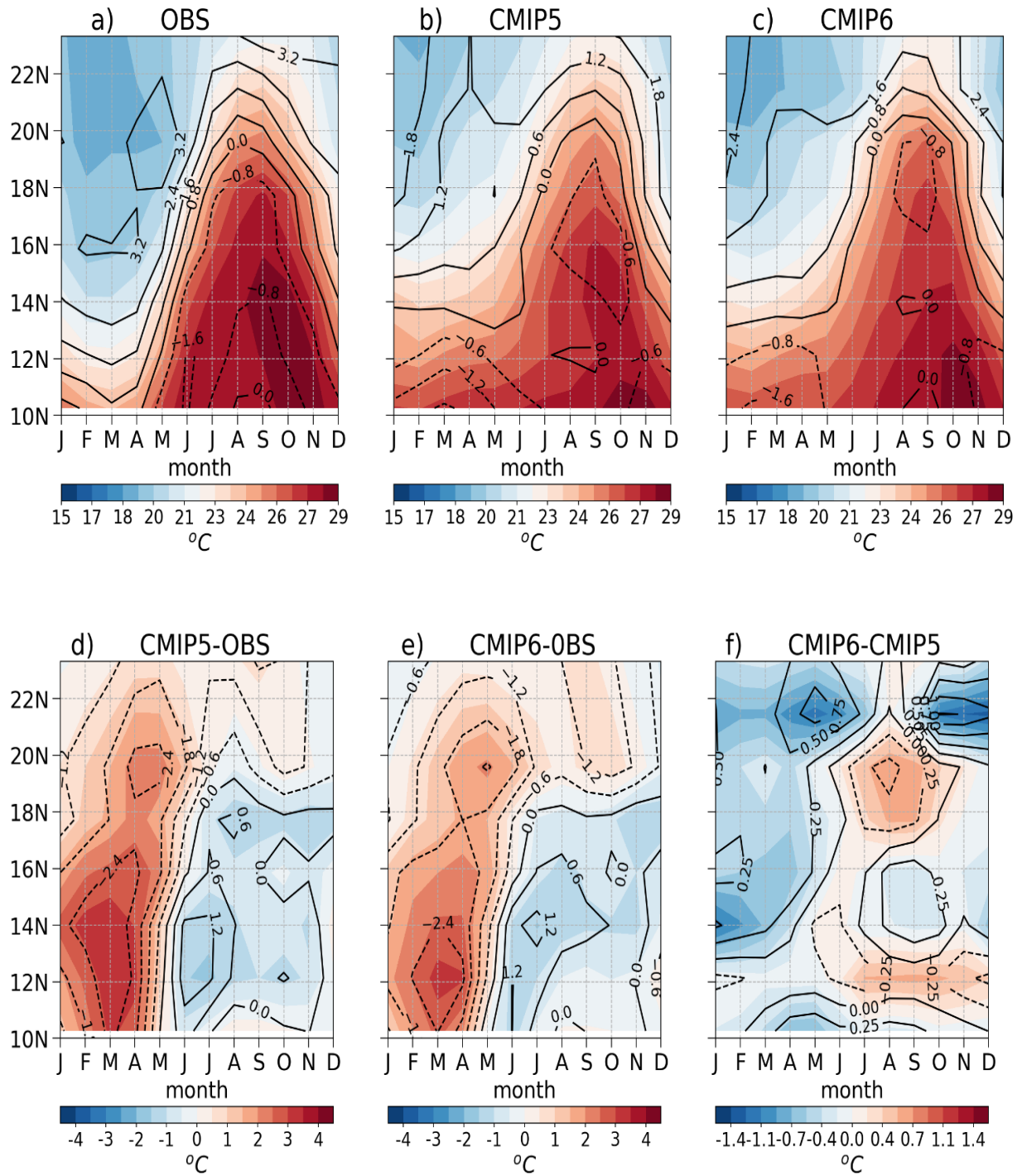


Figure 4.35: Ability of CMIP5 and CMIP6 models in simulating annual cycle of the SST patterns (colour shading) and SST-based upwelling indices (contours) in the Senegal-Mauritania coastal upwelling system.

The analysis of SST and upwelling indices in the GGUS reveals that CMIP models capture some aspects of the system's dynamics but face significant limitations. Both CMIP5 and CMIP6 models (Fig. 4.36b, c) simulate the annual SST cycle but fail to represent its variability adequately. The minimum SST values are overestimated while the maximum SST values are underestimated. The SST-based upwelling index, using SST thresholds below 23°C as an indicator of active upwelling, shows discrepancies. CMIP models fail to accurately replicate observed SST peaks that drive the upwelling dynamics. A comparative analysis of simulated upwelling indices with those derived from ocean reanalysis datasets indicates that Both CMIP5 and CMIP6 better capture the annual cycle of upwelling when aligned with reanalysis data. This suggests that reanalysis datasets provide a more consistent baseline for model validation than observations alone.

CMIP models simulate the annual cycle of SST and upwelling but struggle with capturing variability and extreme SST values. CMIP6 shows moderate improvements in simulating upwelling indices, particularly when compared to reanalysis data, but these improvements do not resolve the major biases in SST simulation.

The inability to accurately simulate key seasonal features, like the March peak and the amplitude of variability, highlights areas for improvement in climate model physics and resolution. CMIP6 demonstrates progress in reducing biases in certain periods, but the overestimation of transport and underestimation of variability remain challenges. Model accuracy and biases was analysed with the performance metrics. Based on RMSE and correlation coefficients, CMIP6 models outperform CMIP5 in SST simulations, with reduced biases (up to 0.9°C in SMUS). In SMUS (Fig. 4.39a, b), 45% of CMIP5 models and 44% of CMIP6 models simulate wind speed accurately.

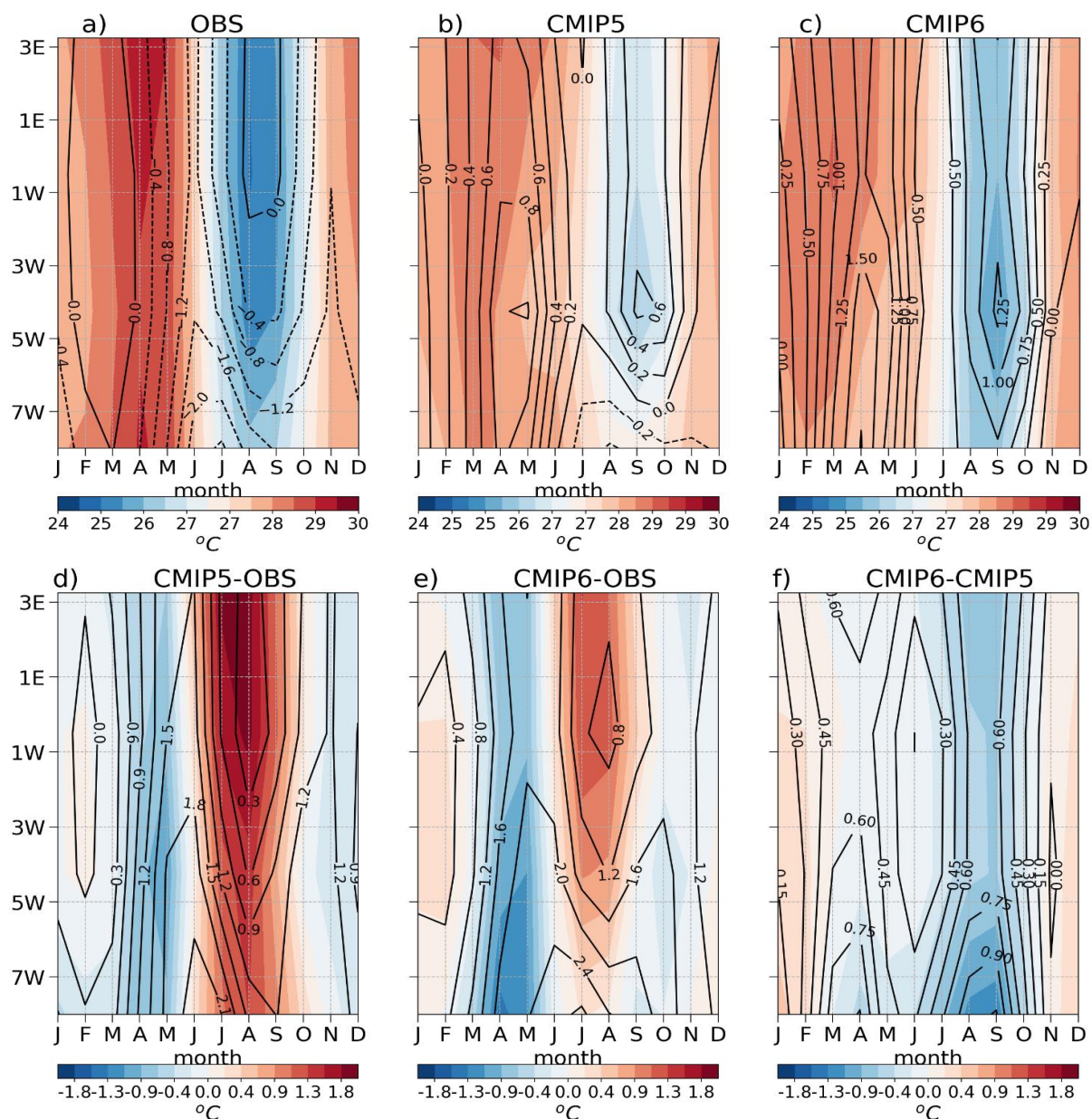


Figure 4.36: Ability of CMIP5 and CMIP6 models in simulating observed SST patterns (colour shading) and SST-based upwelling indices (contours) in the Gulf of Guinea coastal upwelling system.

In GGUS (Fig. 4.37b, c), these values increase to 45% and 52%, respectively. The top-performing models in simulating SST in the SMUS are CNRM-CM5-2 (CMIP5) and E3SM-1-1 (CMIP6), and in the GGUS are CNRM-CM5-2 (CMIP5) and GFDL-ESM4 (CMIP6). While the top-performing models in simulating wind stress in both SMUS and GGUS are IPSL-CM5B-LR, MPI-ESM1-2-LR (CMIP5) and BCC-ESM1 (CMIP6). Both CMIP generations face difficulties in accurately modeling coastal processes, with high proportions of less accurate models (>40%). CMIP6 models show improvements in upwelling wind stress, with 28% of CMIP5 and 59% of CMIP6 models aligning closely with observations in SMUS. For GGUS, the figures are 32% for CMIP5 and 53% for CMIP6. While CMIP6 models improve upon CMIP5 in simulating SST and wind-driven upwelling indices, challenges persist in capturing peak upwelling and variability, particularly in the GGUS and southern SMUS. Enhanced resolution and better parameterizations are required to address persistent biases and better simulate upwelling dynamics in these regions.

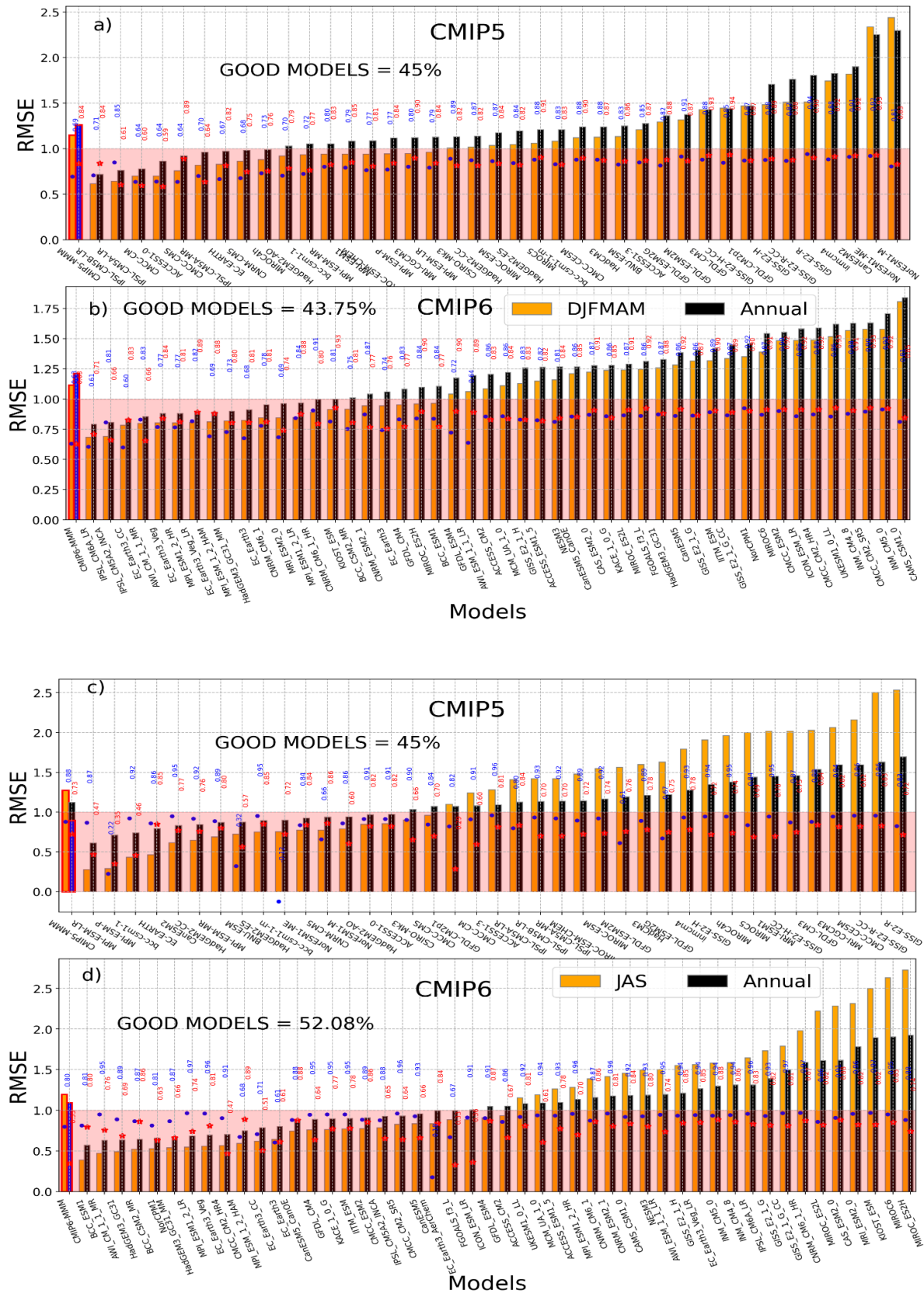


Figure 4.37 CMIP5 and CMIP6 model ranking in simulating wind speed in the Senegal-Mauritania and Gulf of Guinea coastal upwelling regions.

4.3.5 Future Projection of Northwest African and Gulf of Guinea Coastal Upwelling

Previous studies (Sylla *et al.*, 2019; Varela *et al.*, 2022; Vázquez *et al.*, 2024) have reported mixed predictions regarding the future variability of upwelling along the Northwest African coasts, with projections ranging from increasing and decreasing trends to little or no change. To address this uncertainty, we analyzed future trends in upwelling in the SMUS and GGUS using different CMIP6 climate change scenarios. Among the seven SSP-based scenarios included in CMIP6 climate projections, three were selected for this study: SSP585, SSP370, and SSP245. The analysis initially considered all available models for each scenario but later focused on the highest-performing models identified in previous historical simulations. The future trends of upwelling-favorable winds and SST were examined for each upwelling system.

In the SMUS, all models and scenarios indicate no significant decreasing trends in SST (Fig. 4.38a), which are associated with almost constant wind patterns, including wind speed, wind stress, and Ekman transport, during the winter-spring upwelling season (Fig. 4.38b, c, d). These results suggest that upwelling in the SMUS is likely to remain relatively stable despite anthropogenic climate change. However, the highest-performing models project a significant increase in SST (+2.5°C) by the end of the 21st century under the three scenarios (Fig. 4.38e). This warming is accompanied by a decreasing trend in upwelling wind stress (Fig. 4.38h), implying potential weakening of upwelling intensity. In the GGUS, SST during the summer is projected to increase by +1.2°C to +1.5°C by the end of the 21st century under the selected scenarios (Fig. 4.38a).

Wind speed and total wind stress show weak increasing trends (Fig. 4.38b, c). Notably, the Ekman transport, a key indicator of wind-driven upwelling is projected to increase significantly, with trends of up to +1 m²/s, particularly under the SSP5-8.5 and SSP3-7.0 scenarios (Fig. 4.38d). This suggests that wind-driven upwelling may intensify in the GGUS despite rising

SSTs. The highest-performing models (Fig. 4.38e, i) consistently indicate significant increasing trends in both SST and Ekman transport across all three scenarios. These results underscore the importance of selecting well-performing models for more reliable projections.

The analysis highlights contrasting futures for the SMUS and GGUS upwelling systems. While the SMUS is expected to experience moderate changes in upwelling intensity despite warming SSTs, the GGUS may see more pronounced increases in wind-driven upwelling alongside higher SSTs. These findings reflect the complex interplay between wind patterns, SST, and upwelling processes under future climate scenarios.

This study investigated the uncertainties in CMIP models with respect to the simulation of SST-wind interactions in the Northwest African coastal upwelling regions. Using various statistical tools, we assessed the performance of CMIP5 and CMIP6 models in reproducing SST, wind speed components, upwelling favourable wind stress, and the annual cycle of upwelling in the Senegal-Mauritania and Guinea Gulf coastal upwelling systems. CMIP6 models generally show improvements over CMIP5 in simulating upwelling metrics and annual cycles based on SST and wind data. However, many models still exhibit biases similar to those in CMIP5, particularly in capturing upwelling favourable wind stress and in accurately representing SST in the southern part of the SMUS and GGUS.

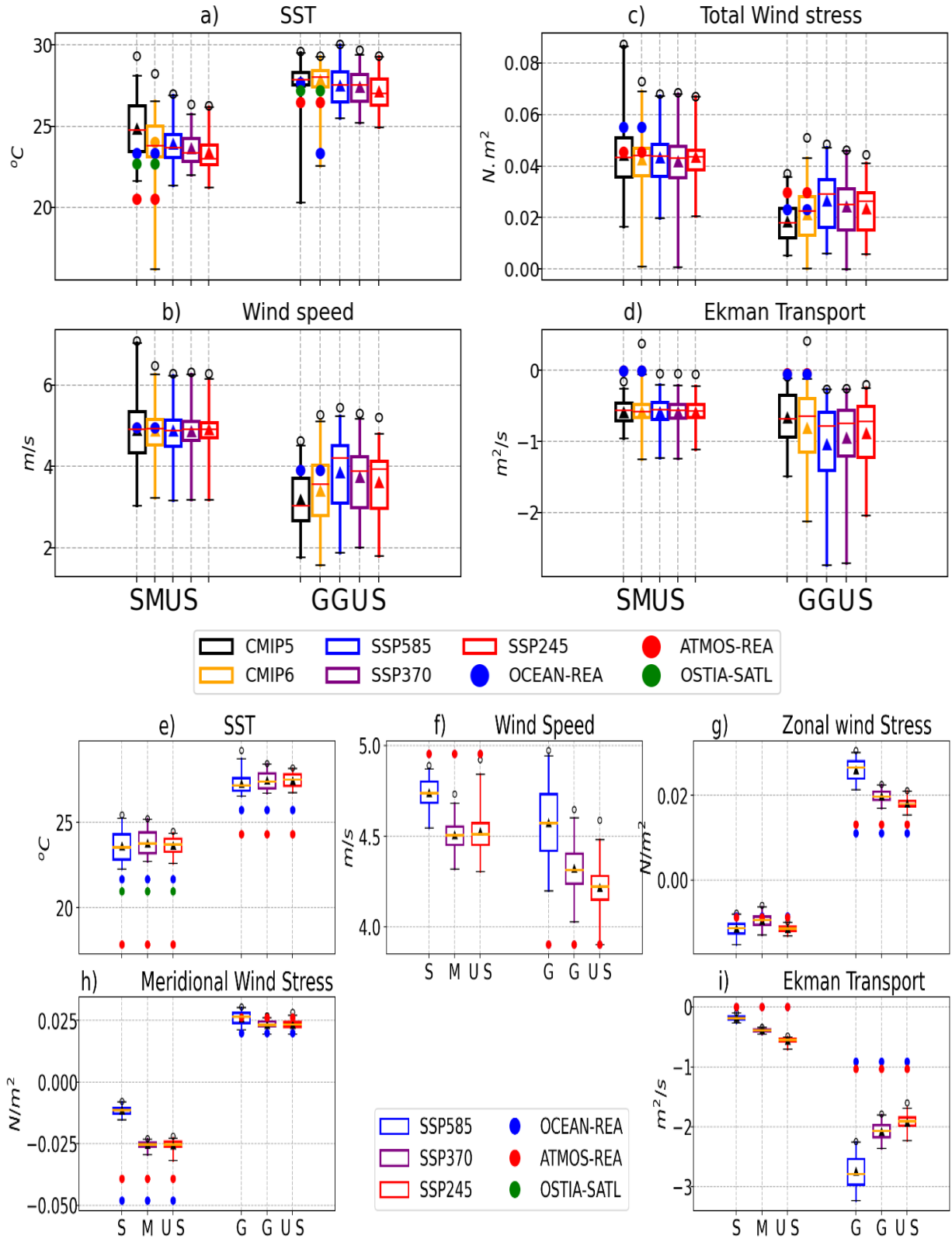


Figure 4.38: Trends of upwelling metrics under CMIP6 scenarios (SSP585, SSP370, SSP245) in the Northwest African and Gulf of Guinea coastal upwelling systems.

Despite progress, CMIP models struggle to accurately capture the physical mechanisms, processes and drivers that control SST and wind variability, as well as air-sea interactions in upwelling regions. For example, 56% of CMIP6 models fail to adequately capture the upwelling favourable wind stress in the SMUS and overestimate the SST. Bock *et al.*, (2020) and Chen *et al.*, (2021) found that CMIP6 models show improvements in extreme precipitation indices, but regional biases in temperature and precipitation simulations. Sylla *et al.*, (2019) projected a moderate decrease in SMUS winter/spring upwelling intensity due to reduced wind forcing and changes in regional low-pressure systems. Otero *et al.*, (2023) found no statistically significant trends in upwelling index or temperature in the Canary upwelling system (CUS) despite global warming.

Valera *et al.*, (2022) predicted a northward shift of upwelling systems by the end of the 21st century, while Vazquez *et al.*, (2021) found that CMIP6 models tend to overestimate near-shore SST in all Eastern Boundary Upwelling Systems (EBUS) except the Canary upwelling system. Müller *et al.*, (2018) identified SST biases in both lower- and higher-resolution MPI models, but noted improvements in high-resolution versions. Fidler *et al.*, (2020) observed continuous improvements in tropical precipitation across CMIP phases, but noted that improvements were not consistent across all temporal and spatial scales. Vazquez *et al.*, (2021) showed that high-resolution regional coupled models better reproduce large-scale and mesoscale features of the CUS compared to global and regional models. Zhu and Yang (2020) found that biases persist in CMIP6 models when simulating surface temperature and precipitation, although improvements are observed.

Kim *et al.*, (2020) reported reduced dry biases in high-latitude regions with improved precipitation intensity simulations, but persistent cold biases in extreme cold events. Wehner *et al.*, (2020) found no significant differences between CMIP5 and CMIP6 in the simulation of extreme daily temperature and precipitation at standard resolutions. Polonsky and

Serebrennikov (2018) observed that while wind activity has intensified near the northwest African coast, leading to enhanced local upwelling, the weakening of the northeast trade winds has reduced the upwelling area, offsetting temperature changes. Yves *et al.*, (2021) found increased upwelling-favourable winds in the CUS, but highlighted considerable uncertainty in long-term upwelling trends depending on the EBUS and data sources. Siemer *et al.*, (2021) suggested that stratification and coastal trapped waves may have more significant effects on upwelling intensity and productivity than wind stress alone.

4.4 Predictive Modeling of Upwelling Features Using AI Approach

4.4.1 Simulation of Offshore Ekman and SST-based Upwelling Indices

Predicting coastal upwelling effectively requires accurate forecasting model simulation of SST and wind patterns. This section discusses the outcomes of AI models applied to the task of predicting interannual variability in monthly coastal upwelling using SST-based and Ekman transport. The models were evaluated based on standard statistical metrics such as metrics RMSE, Mean MAE, determination coefficient (R^2) and through visual assessment of the predicted against SSP585 scenario.

The results revealed that AI models provided a significant improvement over SSP585. Almost all the models show good performance (Table 4.3), yielding the lowest RMSE and MAE values alongside the highest score ($R^2 > 70$). This indicates a closer alignment with observations, underscoring the efficacy of integrating AI models features to extract the temporal dynamics of coastal upwelling SST and wind stress anomalies.

4.4.2 Internal Comparison between Machine Learning and Deep Learning Architectures

Table 4.3 Model scores in simulating observed coastal upwelling indices

Region	Model	MAE	MSE	RMSE	R2
21-25N	Random Forest	0.035	0.005	0.070	0.812
	Gradient Boosting	0.031	0.004	0.063	0.846
	LSTM	0.039	0.004	0.065	0.841
	CNN	0.085	0.013	0.113	0.568
	LSTM-CNN	0.040	0.004	0.064	0.851
10-20N	Random Forest	0.032	0.003	0.059	0.944
	Gradient Boosting	0.033	0.004	0.062	0.938
	LSTM	0.044	0.005	0.072	0.915
	CNN	0.060	0.006	0.079	0.896
	LSTM-CNN	0.034	0.003	0.054	0.953
7-2W	Random Forest	0.029	0.003	0.058	0.887
	Gradient Boosting	0.030	0.003	0.059	0.880
	LSTM	0.037	0.004	0.060	0.879
	CNN	0.051	0.006	0.074	0.825
	LSTM-CNN	0.031	0.003	0.052	0.910
2W-2E	Random Forest	0.027	0.003	0.051	0.900
	Gradient Boosting	0.025	0.002	0.048	0.912
	LSTM	0.033	0.004	0.060	0.864
	CNN	0.062	0.007	0.082	0.797
	LSTM-CNN	0.027	0.002	0.049	0.911

Comparatively, the selected AI models represent well the observed Ekman transport and SS-based than SSP585 multi-model mean, which underestimates the observed upwelling indices in both upwelling systems. All the statistical model used are close to observed and show negative RMSE (Table 4.4) computed successively over the training epochs in the different sub-regions, which is more pronounced in the permanent upwelling region (21-25°N). This indicates that the AI models are learning to predict refinement SST and wind anomalies more accurately than the dynamic climate models that are not enable to resolve well coastal processes maybe because of their spatial resolution.

Table 4.4: Model score with SSP scenario multi-model mean

Model	Index	21-25N		10-20N		7-2W		2W-2E	
		RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2
Random Forest	Ekman Transport	0.960	-8.103	0.516	-1.628	0.356	-0.255	0.658	-3.280
Gradient Boosting		0.959	-8.101	0.516	-1.629	0.356	-0.254	0.658	-3.281
LSTM		0.942	-7.782	0.528	-1.754	0.358	-0.268	0.656	-3.251
CNN_		0.934	-7.624	0.539	-1.867	0.322	-0.022	0.568	-2.193
LSTM_CNN		0.965	-8.205	0.525	-1.721	0.336	-0.118	0.621	-2.811
Random Forest	SST-based	2.575	-30.239	1.213	-5.934	0.721	-1.446	0.730	-1.507
Gradient Boosting		2.606	-30.988	1.282	-6.737	0.710	-1.374	0.748	-1.636
LSTM		2.669	-32.565	1.490	-9.455	0.774	-1.820	0.805	-2.055
CNN_		2.477	-27.902	1.245	-6.300	0.745	-1.614	0.751	-1.657
LSTM_CNN		2.614	-31.174	1.260	-6.481	0.719	-1.438	0.754	-1.678

Although the four models used performed well in capturing temporal patterns of upwelling indices, they did not achieve the same level of accuracy. CNN was slightly less precise ($R^2=0.5$) in predicting monthly SST-based and zonal offshore transport variations in the Senegal-Mauritania permanent upwelling region. Including climate indices (e.g., ENSO, ATL3, AMM), RFR and GBR were effectively fallen ($R^2= 0.004$ and 0.005 , respectively) in the temporal prediction of SST anomalies in the eastern of cape Palmas (7W-2W), with RMSE around 0.87 and 0.84, respectively. This result suggests that the large-scale drivers influence negatively the model results.

In addition, to isolate the impact of individual deep learning model on predicting temporal dynamics of upwelling indices, we integrated the LSTM hyperparameters to the CNN shape. This integration resulted an improvement of simulations, with lower RMSE and MAE scores, alongside a higher determination coefficient, compared to an individual LSTM and CNN model. This improvement highlights the hybrid model LSTM-CNN effectiveness in capturing temporal dependencies within the SST and wind stress anomalies data, which are crucial for accurately predicting monthly coastal upwelling scenarios. However, this hybrid model completely fell to capture upwelling indices in the eastern of cape Palmas.

The visual analysis focused on the coherences with the SSP585 projection trends, and the overall resemblance with observation data (Fig. 4.39). The selected models demonstrated a remarkable ability to capture both SST gradients and offshore Ekman transport at fine-scale details using large-scale climate patterns (e.g., ENSO, NAO), and localized cold upwelled structures near the coast, which are essential for accurate representation of coastal upwelling events. The comparative analysis clearly shows the AI regression models' exceptional capability in generating high-resolution forecasts that exhibit a remarkable coherence with observations.

The AI models despite their capacity were inadequately to resolve upwelling indices in the Guf of Guinea, in particular in the east of cape Palmas can be linked to some inputs variables that the models have not successful to resolve their variability and correlations with SST and wind stress components.

These findings underscore the capacity of advanced AI techniques in refining the accuracy of SST-based and Ekman transport predictions, thereby offering significant implications for future advancements and applications of AI tools within the domain of marine sciences. Our analysis reveals the effective capacity of traditional Machine learning and advance deep learning regression models such as Random Forest (RFR), Gradient Boosting (GBR), Long Short-Term Memory (LSTM), Convolutional Neural Network (CNN) and the integration LSTM with CNN architectures, to capture the interannual variability of SST and wind stress patterss (Ekman transport), critical factors of coastal upwelling along the Northwest African coast.

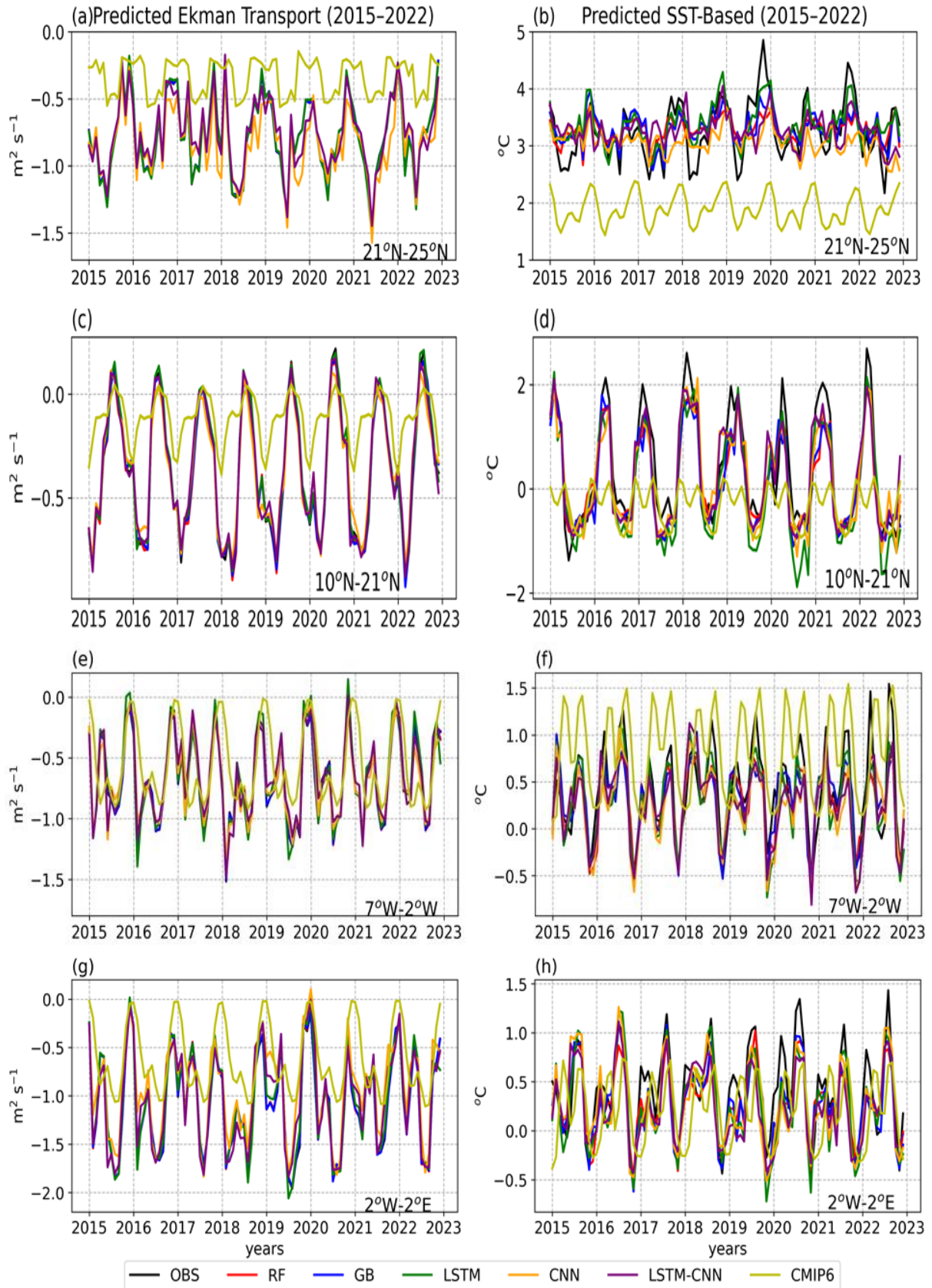


Figure 4.40: Machine learning and deep learning predictions of the interannual variability of upwelling indices including offshore Ekman transport (a, c, e, g) and SST-based in the Senegal-Mauritania (a-d) and Gulf of Guinea (e-h) coastal upwelling systems.

SHAP was used to assess the impacts of model models (Fig 4.40), in particular RFR and GBR on the predictions. In the Senegal-Mauritania coastal upwelling regions, SHAP results show wide spread of SHAP values, mostly positive, especially when SLA is high. This suggests that stronger SLA increases the predicted SST-based upwelling index and offshore Ekman transport. The high values Tugo, Tvgo, tau_x, tau_y push prediction positive, while the high High SSTA often push output lower, possibly indicating warm SSTs correlate with changes in upwelling behavior.

In the seasonal upwelling region (10°N-20°N), the SHAP outputs (Fig. 4.40c, d) show that the higher values of the features push prediction lower while the decreasing of the features seems to increase model capacity to simulate simultaneous both upwelling indices. In the two upwelling cells of the Gulf of Guinea (7°W-2°W and 2°W-2°E), the SHAP plots show more scattered impact but important (Fig. 4.40e-h), suggesting all the selected features play a significant role in modifying upwelling. This shows the complexity of this upwelling and selected models the main driver of this coastal process. However, stronger zonal wind stress was found to increase the predicted SST-based upwelling index or Ekman transport. Climatic Indices such as AMM, NAO, ATL3, NTA, ENSO, SOI, PDO, show Lower Importance with smaller SHAP ranges indicating less influence or indirect influence of large-scale modes (e.g., via wind or current anomalies) on coastal upwelling.

Partial Summary

In summary, the section has evaluated the performance of AI statistical models such as Random Forest, Gradient Boosting, Long Short-Term and Convolutional architectures to simulate Northwest African coastal upwelling indices over SSP585 scenario, including Ekman transport and SST-based. These techniques provide a comprehensive analysis and understanding of

complex oceanographic phenomena, specifically coastal upwelling, which significantly impacts marine ecosystems and regional climate.

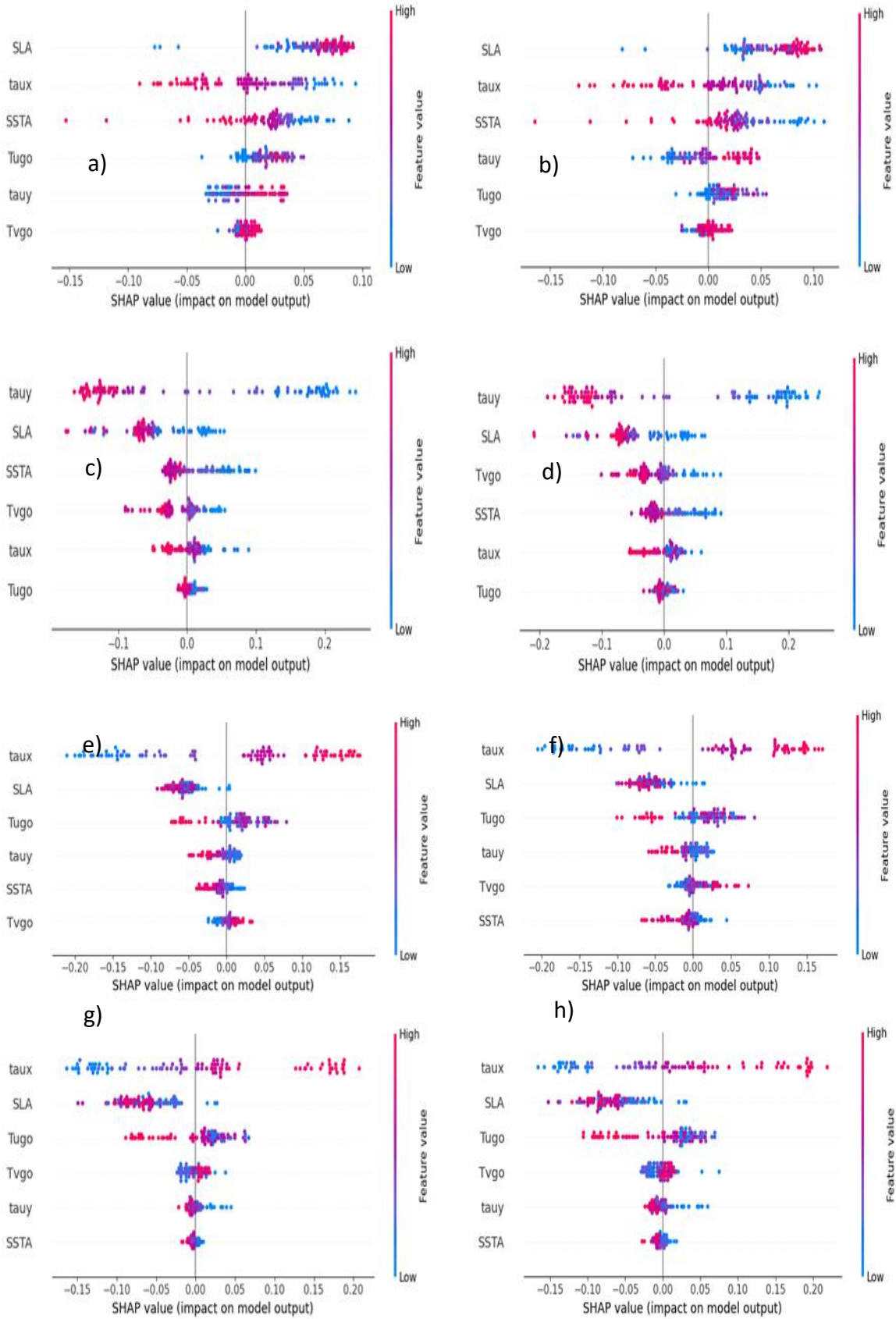


Figure 4.40: SHAP summary plots for the Random Forest (a, c, e, g) Gradient Boosting (b, d, f, h) models used for predicting SST-based upwelling index and Ekman transport in the Senegal-Mauritania (a-d) and and Gulf of Guinea (e-h) coastal upwelling systems.

The adoption of these sophisticated AI models has led to a notable improvement in predicting SST fields, reducing in RMSE and increasing the coefficient of determination. This enhancement over the ML and DL models, underscores the selected models' capability to accurately capture the dynamic and interannual variability of coastal upwelling. All the models have shown to be adept at extracting complex temporal time-series within upwelling regions, unveiling both low-level and high-level features (Krizhevsky *et al.*, 2012), while RNNs, and particularly their extension LSTM networks, capture temporal sequences (Sherstinsky, 2020). This study also investigates the fusion of CNNs and LSTMs into a hybrid model to improve the accuracy and upwelling forecasts (Shi *et al.*, 2015). These results offer opportunities for future research in marine meteorology, highlighting the potential of AI techniques simulating upwelling features and improving climate model predictions in meteorology and climate science. Further investigation employing models that include spatial and temporal dimensions of coastal upwelling will be necessary for enhance the short forecasting and long-term predictions of coastal upwelling.

Using a mixit approach of artificial neural network (ANN) techniques, Kriebel *et al.*, (1998) found difficulties in predicting Northwest coastal upwelling because of weak quantity of the input data. The machine learning (RF, GB) and deep learning (LSTM, CNN) techniques used in this study were applied to predict SST time series and marine heatwaves in the Mediterranean Sea (Bonino *et al.*, 2024), using atmospheric variables are as potential predictors of MHWs. Their results show that all the ML methods performed with minimum RMSEs of about 0.1 °C at a 1st day lead time and maximum values of about 0.8 °C at a 7th day lead time. Their results also show that LSTM has different highest predictive skill in defferent regions at all lead times. They also mentioned that ML techniques show results similar to the dynamical Copernicus Mediterranean Forecasting System (MedFS) for both SST and MHW forecasts, especially in the early forecast days.

These results enhance the comprehension of our model performances in predicting SST gradient in the Northwest African coast. As Bonino *et al.*, (2024), all our models predict the SST gradient with a confidence level greater than 50 % in each region.

Focusing on on the prediction of SST using deep learning model experiements, Snoussi *et al.*, (2024) have recently show the performance of IA models predicting the feature spatio-temporal variability of SST in the Marocco cosatal upwelling region. This result supported the output of our LSTM and LSTM-CNN hybrid in simulating SST anomalies. Simular result was presented by Ronneberger *et al.*, (2015) in the biomedical analysis.

The LSTM-CNN hybrid architecture, revealing its superior capability for high simulations of Ekman transport and SST-based, essential for the precise identification of coastal upwelling. This confirms the results of Ling *et al.*, (2022), who demonstrated tha a multi-task deep learning model can predict the IOD well up to 7-month ahead. Despite, of the high performance of the selected AI models, they struggle to capture well the extreme event of upwelling and need more conceptions.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

As part of the efforts to improve understanding of mechanisms and variability of coastal upwelling in the eastern Atlantic boundary systems, this study results examined the new oceanographic and atmospheric modulators of the predictability of Northwest African coastal upwellings through observations reanalyses and climate model outputs.

The characterization of the Senegal-Mauritania and Gulf of Guinea coastal upwelling systems shows an important latitudinal, seasonal and interannual variability that can be associated to several local and remote atmospheric and oceanographic forcings such wind-driven offshore Ekman transport, wind stress curl driven coastal upwelling, onshore geostrophic flow, interactions between regional currents and coastline and the equatorial dynamics via the propagation of Kelvin waves and poleward propagating of coastal-trapped waves. The critical role of mesoscale factors confirms that both coastal upwelling systems are complex systems that only one factor can not explain. For the interannual variability, the analysis was focused on the role played by large-scale climate modes (e.g., ENSO, ATL3, AMM). The study analysis showed the recent changes in the upwelling systems associated with climate variability and global warming and address possible responses of upwelling systems in future scenarios. These results show different trends between SST-anomalies and upwelling favourable wind stress.

The Evaluation of the prolonged, discrete and short-term SST events reveals that MHWs are an important stressor that can modulate the dynamical process, spatial and temporal variability, and ecosystem productivity in the Senegal-Mauritania and Gulf of Guinea coastal upwelling systems. However, these events deserve special attention for monitoring and management of

coastal marine ecosystems, and the predictability of coastal upwelling, local weather patterns and regional climate variability.

The assessment of uncertainties and performances climate models shows that the generations of climate models continue to simulate coastal upwelling process with biases despite improvements observed in some CMIP6 mult-model mean. Many models (e.g.s, GISS, CESM2, MIROC6) still fall to capture well upwelling features over Senegal-Mauritania and Gulf of Guinea coastal upwelling regions and call for using powerfull tools to improve climate model simulations. Evaluating the performance of the predictive modeling with AI approach, the results show a statistically significant perfonmances of Machine Learning and Deep learning models in simulating the interannual variability of coastal upwelling indices including offshore Ekman transport and SST-based. The models (Random Forest, Gradient Boosting, LSTM and CNN) predict well both upwelling indices, show climate model biases. All the four statistical AI model experiments have shown good simulations with a best performance observed with LSTM-CNN coastal processes and upwelling features and air-sea interactions. A better understanding of upwelling drivers will contribute to enhance the monitoring and weather predictability and a more comprehensive assessment of the ecosystem variability in that region.

5.2 Recommendations

The results of this study provide valuable insights of the ocean-atmosphere interactions in modulating Northwest African upwelling systems. However, the study was limited by the availability of station data due to the lack of observations along the West African coasts, as well as the unwillingness of data managers to share this data with researchers at a low cost. Through the results of this study, we recommend the regional solidarity and low-coast meteorology and marine data sharing to regional researchers.

This study shows the sensitivity of coastal upwelling systems to the short and discrete SST events, the vulnerability of coastal ecosystems that can impact fisheries and have important socio-economic consequences impacting food security and livelihoods. These consequences call the strengthening of regional ocean monitoring and forecasting to predict and track MHWs and integrated MHW alerts into the national and regional climate disaster risk assessment platforms (e.g., ACMAD, AGRHYMET).

The literature review and results of this study show the limitations of global climate models as well as the single regional ocean or atmosphere in simulating coastal upwelling features. This study recommends developing regional coupled models that will consider both physical mechanisms and biogeochemical processes to improve upwelling simulations.

The machine and deep learning statistical modeling show good performances in simulating the wind-SST interactions at the interin the Northwest African coastal upwelling regions. It will be better to test both temporal and spatial simulations of AI technology in the upwelling regions.

5.3 Contribution to Knowledge

Characterizing the Northwest African coastal upwelling, this study contributes to an emerging understanding of the Eastern Atlantic boundary upwelling mechanisms, including Senegal-Mauritania and Gulf of Guinea beyond bulk ocean cooling and warming. Assessing the impacts of MHW of coastal upwelling dynamics and productivity, the results of this study provide valuable insights into the sensitivity of coastal upwelling to extreme temperature events such as MHWs, with practical implications for the seasonal predictability of local weather patterns and regional climate variability, and the implementation of monitoring measures for marine ecosystems, agricultural and water resource planning, in regions where rainfall timing is critical, disaster risk reduction, considering the potential for altered hydroclimatic extremes

under future warming scenarios. This aligns with recent calls for improved mechanistic attribution of MHWs in coastal and marginal seas (Pastor and Khodayar, 2023).

Assessing the performances and uncertainties of climate models, the findings the study provide valuable insights into the sensitivity and continue limitations of the last generations of climate models in capturing the dynamical process of coastal upwelling. This calls for improvement of model simulations, over coastal upwelling regions. Evaluating the performances machine learning and deep learning models, this study promotes the use of AI tools and techniques in marine metrology and climate science for a better forecasting and prediction of local weather, regional climate and the phenomena associated such as coastal upwelling.

5.4 Suggestions for Future Research

The results of this study have demonstrated that local marine heatwaves are the new stressors of coastal upwelling dynamics and productivity over Northwest Africa, and provides an opportunity to improve forecasts of upwelling and short-term SST extremes.

The findings of this study also demonstrated the limitations of global climate models in simulating coastal upwelling processes and features in the Northwest Africa. This opens opportunities to develop regional ocean-atmosphere coupled models that consider physical mechanisms and biogeochemical processes. These models can improve the outputs of single regional models and global global climate simulations. The results of this study also show that Artificial Intelligence statistical model such as Random Forest, Gradient Boosting, LSTM and CNN performed well in simulating the interannual variability of upwelling in th SMUS. The machine learning and deep learning statistical models demonstrated the ability of AI technology to enhance dynamical climate model simulations in the small local upwelling regions. Though the performance of these models in simulating upwelling indices could be improved (using spatial and temporal grids) to minimize their spatial and temporal biases.

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APENDICES

Appendix A: Figures

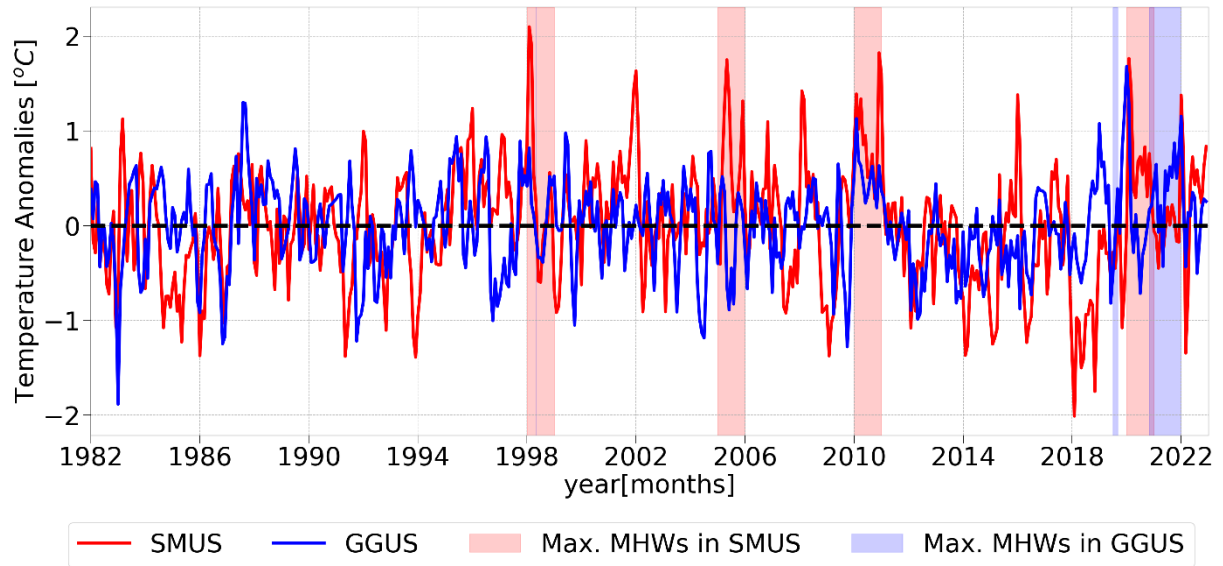


Figure A1: Detrend SST anomalies in the Senegal-Mauritania (red curve) and Gulf of Guinea (blue curve) upwelling systems.

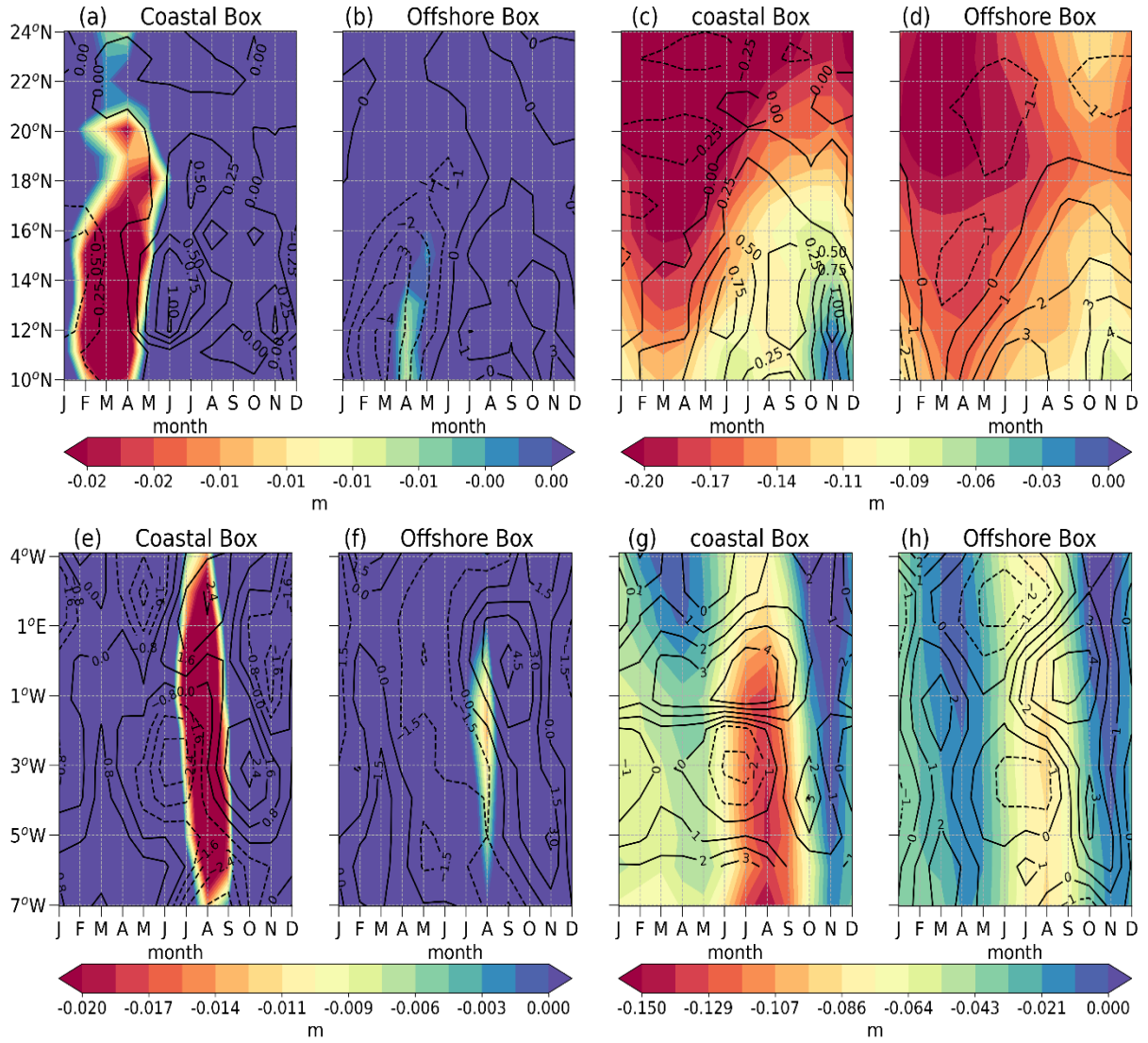


Figure A2: a-b Seasonal cycle of sea level anomaly (SLA), Sea surface height (SSH) upwelling indices based on SLA and SSH used to track wave propagations in the Senegal-Mauritania and Gulf of Guinea coastal upwelling systems.

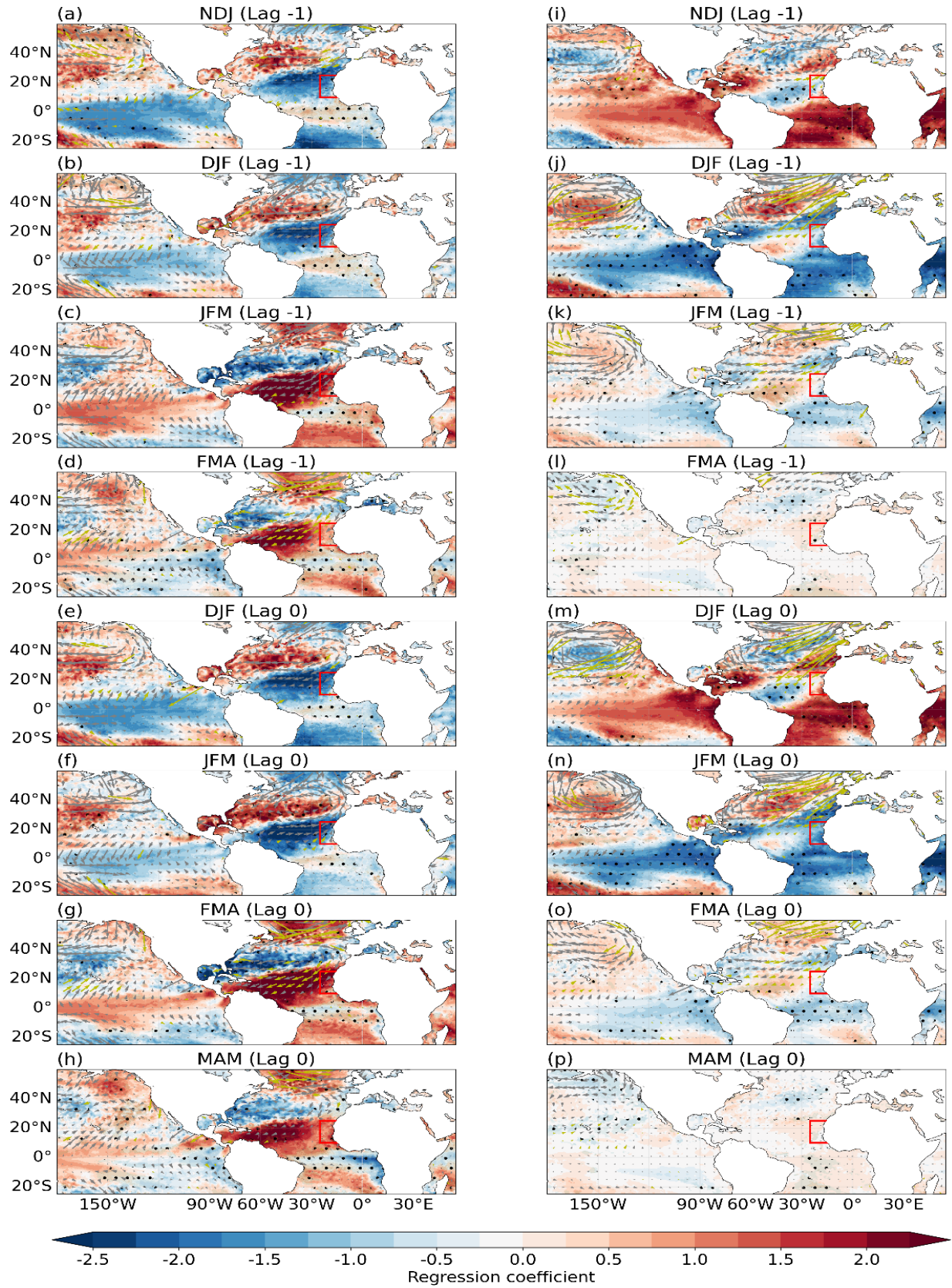


Figure A3: Regression maps between SST and wind stress anomaly fields and leading modes during the extreme MHW episodes in the Senegal Mauritania coastal upwelling system at 90% of confidence interval.

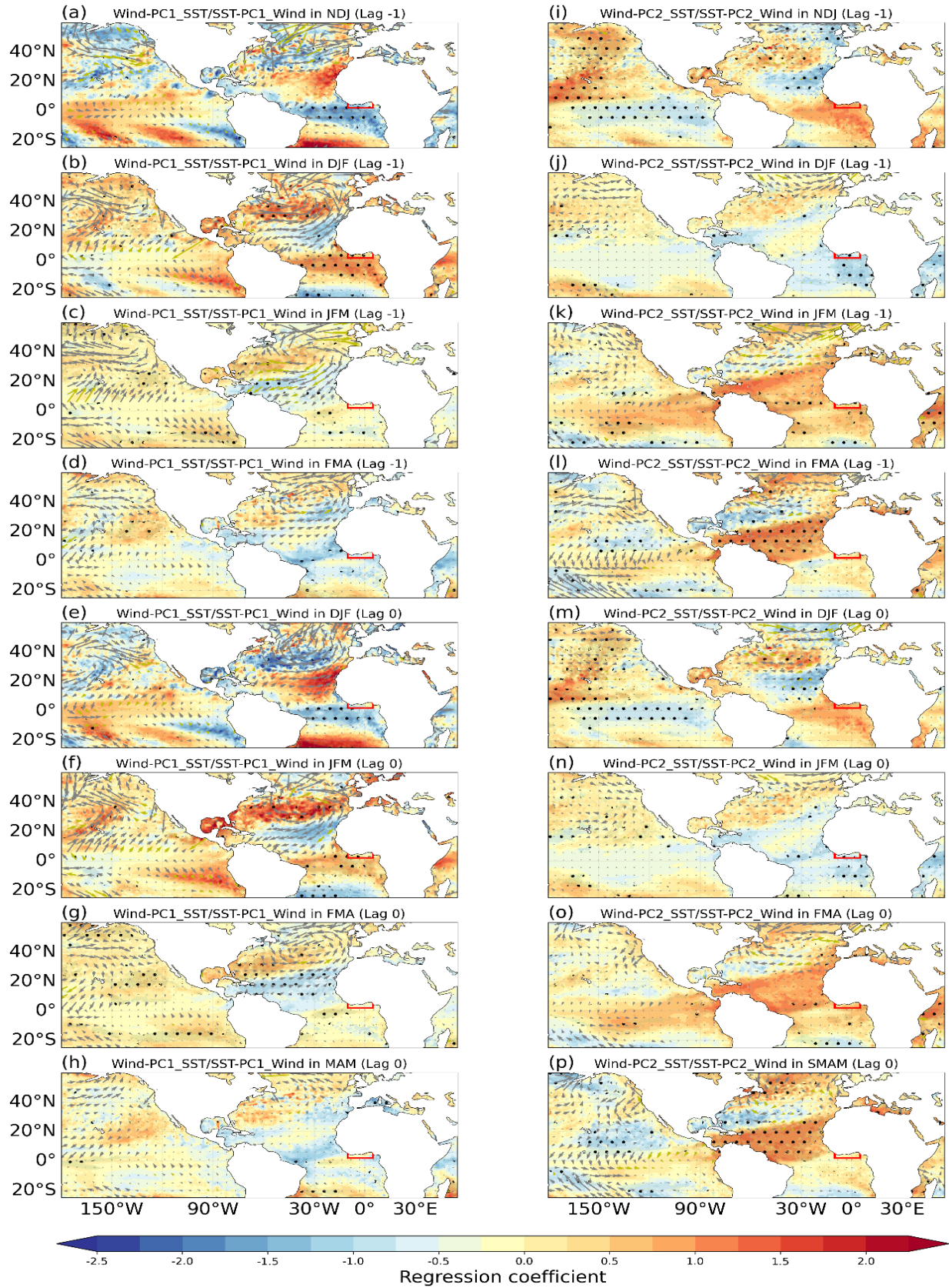


Figure A4: Regression maps between SST and wind stress anomaly fields and the leading modes during the extreme MHW episodes in the Gulf of Guinea coastal upwelling system at 90% of confidence interval.

Appendix B: Tables

Table B1: Observational and Reanalysis Datasets

Data set	Type	Spatial resolution	Variables	Period
ERSST-v3b	Observation	2° x 2°	SST	1980-2022
HadISST	Observation	1° x 1°	SST	1980-2022
ORAS5	Ocean reanalysis	0.25° x 0.25°	SST, wind stress	1980-2022
GLORYS)	Ocean reanalysis	0.083° x 0.083°	SST, wind stress	1993-2020
COBE	Observation	1°x1°	SST	1990-2022
ERA20C	Atmospheric reanalysis	1° x 1°	SST, winds	1980-2010
NOAA20CR	Atmospheric reanalysis	1° x 1°	Winds	1980-2012
ERA-Interim	Atmospheric reanalysis	0.75° x 0.75°	SST, winds	1980-2018
ERA5	Atmospheric reanalysis	0.25° x 0.25°	SST, winds	1980-2022
NCEP	Atmospheric reanalysis	2° x 2°	SST, winds	1980-2022
JRA-55	Atmospheric reanalysis	0.25° x 0.25°	Winds	1980-2022
OSTIA	Satellite	0.05° x 0.05°	SST	1982-2022
NOAA	Satellite	4km x 4km	Ocean Colour	1997-2022
NOAA-CPC	Climate Indices		ENSO, NAO, AMM, NOI, NTA, AMO, PDO, PNA, SOI	1982-2022

Table B2: CMIP5 Model Outputs Used in this Study

Model name	Ocean resolution (°latx°lon) and vertical levels (L)	Atmosphere resolution (°lat x °lon) and vertical levels	horizontal resolution (°lon) and Variables (historical)
ACCESS-1.0	1.0×1.0, L50	1.875×1.25, L38	SST, Wind
ACCESS-1.3	1.0×1.0, L50	1.875×1.25, L38	SST, Wind
BCC-CSM1-1	1.0×1.0, L40	2.8×2.8, L26	SST, Wind

BCC-CSM1-1-M	1.0×1.0, L40	1.125×1.125, L26	SST, Wind
BNU-ESM	0.9×1.0	2.8×2.8	Wind
CanCM4	1.4×0.9, L40	2.8×2.8, L35	SST, Wind
CanESM2	1.4×0.9, L40	2.8×2.8, L35	SST, Wind
CCSM4	1.125×0.6	1.25×0.9	SST
CESM1-BGC	1.125×0.6	1.25×0.9	SST
CESM1-CAM5	1.125×0.6	1.25×0.9	SST
CESM1-CAM5-FV2	1.125×0.6	1.25×0.9	SST
CESM1-FASTCHEM	1.125×0.6	1.25×0.9	SST
CESM1-WACCM	1.125×0.6	2.5×1.9	SST
CMCC-CESM	2.0×1.875	3.7×3.7	SST, Wind
CMCC-CM	2.0×1.875	0.7×0.7	SST, Wind
CMCC-CMS	2.0×2.0	1.875×1.875	SST, Wind
CNRM-CM5	1.0×0.8	1.4×1.4, L31	SST, Wind
CNRM-CM5-2	1.0×0.8	1.4×1.4, L31	SST, Wind
CSIRO-Mk3-6-0	1.875×0.9, L18	1.875×1.875, L31	SST, Wind
EC-EARTH	1.0×0.8	1.125×1.125	SST, Wind
ESLASG-g2	2.8 × 2.8 L26	1.0×1.0 L30	SST
FGOALS-s2	2.8 × 2.8 L26	1.0×1.0 L30	SST
fio-esm	1.125×0.6	2.8×2.8	SST
FIO-ESM	1.125×0.6	2.8×2.8	SST
GFDL-CM2p1	1.0×1.0, L50	2.5×2.0	SST, Wind
GFDL-CM3	1.0×1.0, L50	2.5×2.0	SST, Wind
GFDL-ESM2G	1.0×1.0, L63	2.5×2.0	SST, Wind
GFDL-ESM2M	1.0×1.0, L50	2.5×2.0	SST, Wind
GISS-E2-H	2.5×2.0	2.5×2.0	SST, Wind
GISS-E2-H-CC	1.0×1.0	1.0×1.0	SST, Wind
GISS-E2-R	2.5×2.0	2.5×2.0	SST, Wind
GISS-E2-R-CC	1.0×1.0	1.0×1.0	SST, Wind
HadCM3	1.25×1.25, L20	3.7×2.5, L19	SST, Wind

HadGEM2-CC	1.0×1.0 L40	1.875×1.25, L60	SST, Wind
HadGEM2-ES	1.0×1.0	1.875×1.25, L38	SST, Wind
HadGEM2-AO	1.0×1.0, L40	1.875×1.25, L38	SST, Wind
INMCM4	0.8×0.4	2.0×1.5	SST, Wind
IPSL-CM5A-LR	2.0×1.875, L31	3.7×1.875 L39	SST, Wind
IPSL-CM5A-MR	1.6×1.4, L31	2.5×1.3 L39	SST, Wind
IPSL-CM5B-LR	2.0×1.875, L31	3.7×1.875, L39	SST, Wind
MIROC4h	0.3×0.2	0.56×0.56	SST, Wind
MIROC5	1.6×1.4, L50	1.4×1.4, L40	SST, Wind
MIROC-ESM	1.4×0.9, L44	2.8×2.8, L80	SST, Wind
MIROC-ESM-CHEM	1.4×0.9, L44	2.8×2.8, L80	SST, Wind
MPI-ESM-LR	1.5×1.5, L40	1.875×1.875, L47	SST, Wind
MPI-ESM-MR	0.4×0.4, L40	1.875×1.875, L47	SST, Wind
MPI-ESM-P	1.5×1.5, L40	1.875×1.875, L47	SST, Wind
MRI-CGCM3	1.0×0.5, L51	1.125×1.125, L48	Wind
MRI-ESM1	1.0×0.5, L51	1.125×1.125 L48	SST, Wind
NorESM1-M	1.125×0.6, L53	2.5×1.875, L26	SST, Wind
NorESM1-ME	1.125×0.6, L53	2.5×1.875, L26	SST, Wind
Total models used			47, 40

Table B3: CMIP6 Model Outputs used in this Study

Model name	Ocean horizontal resolution, vertical levels, grid cells	Variables			
		Historical	SSP2-4.5	SSP3-7.0	SSP5-8.5
ACCESS-CM2	360 x 300, L50, top grid cell 0-10 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
ACCESS-ESM1-5	360 x 300, L50, top grid cell 0-10 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
AWI-CM-1-1-MR	L46, top grid cell 0-5 m	Wind, SST	SST	Wind, SST	Wind, SST

AWI-CM-1-1-LR	L46, top grid cell 0-5 m	Wind, SST				
BCC-CSM2-MR	360 x 232, L40, top grid cell 0-10 m					
BCC-ESM1	360 x 232, L40, top grid cell 0-10 m	Wind, SST				
CAMS-CSM1-0	360 x 200, L50, top grid cell 0-10 m	Wind, SST	Wind	Wind, SST	Wind, SST	Wind, SST
CAS-ESM2-0	362 x 196, L30, top grid cell 0-10 m	Wind, SST				
CanESM5-CanOE	361 x 290, L45, top grid cell 0-6.19 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST	Wind, SST
CanESM5	362 x 292, L41, top grid cell 0-10 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST	Wind, SST
CESM2	320x384, L60, top grid cell 0-10 m	SST	SST	SST	SST	
CESM2-FV2	320x384, L60, top grid cell 0-10 m	SST				
CESM2-WACCM	320x384, 60 levels, top grid cell 0-10 m	SST	SST	SST	SST	
CESM2-WACCM-FV2	320x384, L60, top grid cell 0-10 m	SST				
CIesm	320 x 384, L60, top grid cell 0-10 m	SST	SST			SST
CMCC-CM2-HR4	1442 x 1051, L50, top grid cell 0-1 m	Wind, SST				
CMCC-CM2-SR5	62 x 292, L50, top grid cell 0-1 m	Wind, SST				Wind, SST
CMCC-ESM2	362 x 292, L50, top grid cell 0-1 m	Wind, SST	Wind, SST			Wind, SST
CNRM-CM6-1-HR	1442 x 1050, L75, top grid cell 0-1 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST	Wind, SST
CNRM-CM6-1	362 x 294, L75, top grid cell 0-1 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST	Wind, SST
CNRM-ESM2-1	362 x 294, L75, top grid cell 0-1 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST	Wind, SST

E3SM-1-0	60 km to 30 km, SST L60, top grid cell 0-10 m					
E3SM-1-1	60 km to 30 km, SST L60, top grid cell 0-10 m					
E3SM-1-1-ECA	60 km to 30 km, SST L60, top grid cell 0-10 m					
EC-Earth3	362 x 292, L75, top grid cell 0-1 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST	
EC-Earth3-AerChem	362 x 292, L75, top grid cell 0-1 m	Wind, SST		Wind, SST		
EC-Earth3-CC	362 x 292, L75, top grid cell 0-1 m	Wind, SST	Wind, SST			Wind, SST
EC-Earth3-Veg	362 x 292, L75, top grid cell 0-1 m	Wind, SST	Wind, SST	Wind, SST		Wind, SST
EC-Earth3-Veg-LR	362 x 292, L75, top grid cell 0-1 m	SST	Wind, SST	Wind, SST		Wind, SST
FGOALS-f3-L	360 x 218, L30, top grid cell 0-10 m	Wind, SST	Wind, SST	SST		Wind, SST
FGOALS-g3	360 x 218, L30, top grid cell 0-10 m	SST				
FIO-ESM-2-0	320 x 384, L60, top grid cell 0-10 m	SST				SST
GFDL-CM4	1440 x 1080, L75, top grid cell 0-2 m	Wind, SST	Wind, SST			Wind, SST
GFDL-ESM4	720 x 576, L75, top grid cell 0-2 m	Wind, SST	Wind, SST	Wind, SST		Wind, SST
GISS-E2-1-G-CC	288 x 180, L32, top grid cell 0-10 m	Wind, SST				
GISS-E2-1-G	288 x 180, L32, top grid cell 0-10 m	Wind, SST	Wind, SST	Wind, SST		Wind, SST
GISS-E2-1-H	360 x 180, L26, top grid cell 0-10 m	SST				
HadGEM3-GC31-LL		Wind, SST	Wind, SST			Wind, SST

HadGEM3-GC31-MM		Wind			Wind, SST
ICON-ESM-LR	40 km, L40, top grid cell 0-12 m	Wind, SST			
IITM-ESM	360 x 200, L50, top grid cell 0-10 m	Wind, SST	Wind	Wind	Wind, SST
INM-CM4-8	360x318, L40, sigma vertical coordinate	Wind, SST	Wind, SST	Wind, SST	Wind, SST
INM-CM5-0	720x720, L40,	Wind, SST	SST	Wind, SST	Wind, SST
IPSL-CM5A2-INCA	182 x 149, L31, top grid cell 0-10 m	Wind, SST			
IPSL-CM6A-LR	362 x 332, L75, top grid cell 0-2 m	Wind, SST		Wind	
KACE-1-0-G	360 x 200, L50, top grid cell 0-10 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
KIOST-ESM	360 x 200, L52, top grid cell 0-2 m	Wind, SST	Wind, SST		Wind, SST
MCM-UA-1-0		Wind, SST	Wind, SST	Wind, SST	Wind, SST
MIROC6	360 x 256, L63, top grid cell 0-2 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
MIROC-ES2L	360 x 256, L63, top grid cell 0-2 m	Wind, SST	SST	SST	SST
MPI-ESM-1-2-HAM	256 x 220, L40, top grid cell 0-12 m	Wind, SST		Wind, SST	
MPI-ESM1-2-HR	802 x 404, L40, top grid cell 0-12 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
MPI-ESM1-2-LR	256 x 220, L40, top grid cell 0-12 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
MRI-ESM2-0	360 x 364, 61 levels, top grid cell 0-2 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
NESM3	362 x 292, L46, top grid cell 0-6 m	Wind, SST	SST		Wind, SST
NorCPM1	320 x 384, L53, top grid cell 0-2.5 m	Wind, SST			

NorESM2-LM	360 x 384, L70, top grid cell minimum 0-2.5 m	SST	SST	SST	SST
NorESM2-MM	360 x 384, L70, top grid cell minimum 0-2.5 m	SST			
SAM0-UNICON	320 x 384, L60, top grid cell 0-10 m	SST			
TaiESM1	320x384, L60, top grid cell 0-10 m	SST			
UKESM1-0-LL	360 x 330, L75, top grid cell 0-1 m	Wind, SST	Wind, SST	Wind, SST	Wind, SST
Total of Models		59	35	30	39

Table B4: Correlation Coefficients Between Climate Indices and Upwelling Indices

DJF	Ekman Transport Index in SMUS					SST Upwelling Index in GGUS				
	Lag 2	Lag 1	Lag 0	Lead 1	Lead 2	Lag 2	Lag 1	Lag 0	Lead 1	Lead 2
ENSO+	-0.51	0.91	0.90	0.84	0.81	0.14	0.97	0.43	0.31	0.26
ENSO-	0.99*	0.98	-0.35	-0.99*	-0.98	-0.68	-0.51	-0.46	0.60	0.80
NAO+	-0.99*	-0.49	-0.99*	0.57	0.97	0.92	-0.49	0.94	-0.20	-0.80
NAO-	0.52	0.96	-0.48	-0.99*	-0.44	0.30	-0.84	-0.35	0.75	0.97
SOI+	-0.96	-0.32	-0.11	0.50	0.93	0.34	0.96	-0.74	0.42	-0.84
SOI-	0.34	0.85	-0.19	0.88	0.58	-0.83	0.52	0.91	-0.24	0.93
ATL3+	0.10	-0.91	-0.96	-0.98	-0.84	-0.60	0.55	0.67	0.72	0.43
ATL3-	0.20	0.23	-0.91	-0.82	-0.45	0.32	0.29	0.99*	0.43	0.83
AMM+	-0.89	-0.81	0.72	0.99*	0.99*	0.99*	0.52	-0.40	-0.87	-0.96
AMM-	-0.41	-0.09	0.99*	0.38	-0.15	0.79	0.56	-0.86	-0.78	-0.34
AMO+	0.06	0.66	-0.55	0.77	-0.64	-0.59	0.99*	0.12	-0.18	0.009
AMO-	0.88	-0.99*	-0.97	-0.91	0.59	-0.82	0.36	0.23	0.79	-0.99*
PDO+	-0.85	-0.99*	-0.95	-0.82	0.0006	0.59	0.94	0.99*	0.55	0.37
PDO-	0.96	0.60	-0.88	0.48	-0.72	-0.99*	-0.46	0.94	-0.62	0.60
ONI+	-0.82	-0.40	0.99*	0.95	0.90	0.32	-0.22	-0.80	-0.59	-0.47
ONI-	0.78	-0.94	-0.89	-0.98	-0.98	-0.81	-0.06	0.68	0.45	0.45
NOI+	-0.33	-0.98	-0.61	0.98	0.52	-0.74	0.23	0.97	-0.22	-0.99*
NOI-	-0.13	0.92	0.80	-0.73	-0.99*	0.85	-0.27	-0.97	-0.07	0.72
PNA+	-0.67	-0.92	0.99*	0.92	0.95	0.26	0.99*	-0.82	-0.64	-0.99
PNA-	0.88	0.63	0.95	0.96	-0.32	-0.99*	-0.89	-0.99*	-0.99*	-0.09
NTA+	-0.94	-0.99*	0.34	-0.89	0.49	0.70	0.88	-0.72	0.99*	-0.05
NTA-	0.75	0.64	-0.30	0.69	0.72	0.33	0.47	-0.77	0.41	0.37

Table B5: Correlation Coefficients Between Climate Indices and Upwelling Indices

MAM	Ekman transport Index					SST upwelling Index				
	Lag 2	Lag 1	Lag 0	Lead 1	Lead 2	Lag 2	Lag 1	Lag 0	Lead 1	Lead 2
ENSO+	0.48	0.53	0.58	0.55	0.47	0.48	0.43	0.38	0.50	0.41
ENSO-	0.82	0.63	0.73	0.81	0.63	-0.79	-0.59	-0.69	-0.77	-0.59
NAO+	-0.99*	-0.83	-0.99*	0.13	-0.84	0.99*	0.72	0.99*	-0.29	0.92
NAO-	0.99*	0.46	-0.99*	-0.75	0.91	-0.99*	-0.64	0.93	0.87	-0.80
SOI+	-0.89	-0.93	-0.98	-0.80	0.79	0.85	0.64	0.95	0.41	-0.99
SOI-	-0.47	-0.93	-0.98	-0.80	0.79	0.85	0.64	0.95	0.41	0.98
ATL3+	-0.14	0.22	0.02	-0.11	-0.62	-0.77	-0.95	-0.87	-0.80	-0.35
ATL3-	-0.43	-0.82	-0.69	-0.34	0.96	0.13	0.96	0.88	0.62	0.82
AMM+	-0.75	-0.89	-0.92	-0.58	-0.99*	0.99*	0.93	0.90	0.99*	0.64
AMM-	0.88	0.99	0.68	0.40	0.91	-0.68	-0.21	0.53	-0.98	-0.63
AMO+	-0.21	-0.39	0.06	-0.09	-0.06	-0.16	0.03	-0.41	-0.27	-0.31
AMO-	0.59	-0.13	0.93	0.99	0.32	-0.34	-0.15	-0.99*	-0.98	0.04
PDO+	0.99*	-0.63	-0.89	-0.87	0.50	-0.99*	0.44	0.97	0.96	-0.28
PDO-	0.01	0.97	0.99*	-0.30	-0.89	-0.52	-0.95	-0.84	0.75	0.53
ONI+	-0.41	-0.27	-0.23	-0.26	-0.20	0.90	0.83	0.81	0.82	0.79
ONI-	0.44	0.44	0.26	0.06	-0.87	-0.15	-0.15	0.04	0.25	0.69
NOI+	-0.99*	-0.23	-0.31	-0.75	-0.66	0.70	-0.41	0.83	0.19	0.06
NOI-	0.99*	0.52	-0.22	0.99*	-0.05	-0.96	-0.82	-0.18	-0.94	-0.35
PNA+	-0.99*	-0.79	-0.97	-0.15	0.97	0.99*	0.80	0.96	0.17	-0.97
PNA-	0.60	-0.82	0.64	-0.68	0.97	-0.82	0.61	-0.84	0.43	-0.85
NTA+	0.78	-0.66	-0.98	-0.99*	-0.97	-0.85	0.57	0.95	0.99*	0.99*
NTA-	-0.99*	-0.99*	0.19	0.96	0.99*	0.97	0.96	-0.44	-0.99*	-0.98

Table B6: Correlation Coefficients Between Climate Indices and Upwelling Indices

JAS	Ekman Transport					SST Upwelling Index				
	Lag 2	Lag 1	Lag 0	Lead 1	Lead 2	Lag 2	Lag 1	Lag 0	Lead 1	Lead 2
ENSO+	0.57	0.92	0.93	0.15	-0.51	0.55	0.008	-0.006	0.97	0.61
ENSO-	-0.99*	-0.38	0.99*	0.99*	0.94	0.75	0.95	-0.75	-0.60	-0.87
NAO+	0.15	0.78	-0.99*	0.97	-0.25	0.81	-0.91	0.57	-0.22	-0.74
NAO-	-0.67	-0.45	0.97	0.68	-0.81	-0.13	0.97	-0.44	-0.99*	0.97
SOI+	-0.51	-0.31	-0.41	-0.99*	-0.45	-0.27	0.90	-0.37	0.63	0.95
SOI-	-0.97	0.87	0.82	-0.92	-0.57	0.83	-0.98	-0.58	0.99*	0.27
ATL3+	0.92	-0.76	-0.98	-0.99*	-0.99*	0.89	0.007	-0.48	-0.69	-0.71
ATL3-	-0.95	-0.80	-0.64	-0.62	-0.53	-0.93	-0.27	-0.03	-0.005	0.10
AMM+	0.97	-0.62	-0.78	-0.88	-0.91	-0.72	-0.33	-0.12	0.07	0.12
AMM-	0.11	-0.93	0.99*	-0.30	-0.95	0.06	-0.98	-0.97	0.46	0.88
AMO+	-0.86	-0.90	-0.09	0.85	0.88	-0.47	-0.39	0.99*	0.49	0.42
AMO-	-0.89	0.62	0.35	-0.99*	0.43	0.83	0.37	-0.99*	0.44	0.57
PDO+	0.61	0.66	0.86	0.99*	-0.47	-0.71	0.66	-0.60	0.08	-0.92
PDO-	0.99*	-0.51	-0.98	0.64	0.94	-0.83	-0.09	0.90	-0.07	-0.57
ONI+	0.76	0.75	0.62	0.69	0.77	0.59	0.61	0.74	0.67	0.57
ONI-	0.71	0.98	0.96	0.99	0.98	0.19	-0.41	-0.32	-0.47	-0.38

NOI+	-0.52	0.78	0.86	0.93	0.95	0.99*	0.06	-0.09	-0.24	-0.31
NOI-	-0.42	-0.31	-0.27	-0.26	-0.27	0.18	0-07	0.03	0.01	0.03
PNA+	-0.41	-0.58	0.96	-0.34	-0.79	-0.76	0.94	-0.51	-0.81	-0.80
PNA-	0.78	-0.57	-0.93	0.78	0.78	-0.91	0.35	0.99*	-0.61	-0.61
NTA+	0.88	0.93	0.86	0.94	0.68	0.19	0.07	0.23	0.04	-0.90
NTA-	-0.91	-0.98	-0.99*	-	0.58	0.15	0.41	0.63	-	0.35

Table B7: Upwelling Indices Used in this Study

Acronyms	Full Name	Definition	Formula	Unit
$M_{(x)}, M_{(y)}$	Zonal Ekman and Meridional Transport	Upwelling index related to offshore wind stress	$M_{(x)} = \frac{\tau^y}{\rho_w f}$ $M_{(y)} = -\frac{\tau^x}{\rho_w f}$	$m^2.s^{-1}$
W_{scd}	Wind-stress curl driven upwelling (Ekman pumping velocity)	Upwelling related to coastal divergence	$W_{scd} = \frac{1}{\rho_w f} \left(\frac{\partial \tau^y}{\partial x} - \frac{\partial \tau^x}{\partial y} \right)$	$m.day^{-1}$
W_t	Total wind-driven upwelling index	Sum of offshore Ekman transport velocity and inshore Ekman (offshore divergence) pumping velocity (coastal divergence)	$W_t = M_{(x,y)} + W_{scd}$	$m.day^{-1}$
CUI	Cumulative upwelling index	Integrated daily upwelling index over the upwelling cycle	$CUI(t) = \sum_{i=0}^t UI(i). \Delta t$	$m^2.s^{-1}$ and $^{\circ}C$
TUM	Total upwelling magnitude	Cumulative upwelling index from the start to the end dates of upwelling season	$TUM = \sum_{END}^{STI} CUI(t)$	$m^2.s^{-1}$ and $^{\circ}C$
SST_{index}	SST gradient	SST difference between offshore and coastal areas	$SST_{ui} = SST_{open-ocean} - SST_{coast}$	$^{\circ}C$

$T_g,$ $UI_{(SLA,SSH)}$	Onshore geostrophic Transport and coastal upwelling index based on the geostrophic flow	Component of geostrophic current that flows from open- ocean to the coast, Coastal divergence based on SLA and SSH	$T_g = \frac{g}{f} \frac{\partial \eta_{al} - \partial \eta_{on}}{d} MLD$ $UI_{(SLA,SSH)} = \left(\frac{\partial vg}{\partial x} + \frac{\partial ug}{\partial y} \right)$ Where $ug = -\frac{g}{f} \frac{\partial \eta}{\partial y}, vg = \frac{g}{f} \frac{\partial \eta}{\partial x}$ η is SSLA or SSH	$m^2.s^{-1}$
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