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Seasonal Oceanographic Conditions and Their Influence on Marine Productivity in Liberia's Exclusive Economic Zone

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FRONT MATTER

Title

Seasonal Oceanographic Conditions and Their Influence on Marine Productivity in Liberia's Exclusive Economic Zone

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Abstract

An oceanographic campaign was conducted in the Liberian Exclusive Economic Zone (EEZ) aboard the research vessel *Al Hassan Al Marrakchi* between January 25 and February 29, 2024. The campaign, a collaboration between COMHAFAT, INRH, and Liberian authorities, aimed to assess fish stocks, study marine biology, and survey the oceanographic conditions of the area. This paper details the methods used, including oceanographic equipment like the CTD, LADCP, ADCP, and Thermosalinograph. It presents findings on the spatial and vertical distribution of key oceanographic parameters. Results show a surface temperature range of 29.6°C to 30.8°C with an east-west gradient, and a strong thermal gradient with depth, indicating the presence of a thermocline. River inflows dictate the distribution of salinity in coastal waters with a notable difference between coastal and offshore waters. The study also examines the distribution of dissolved oxygen, fluorescence (phytoplankton biomass indicator). The campaign confirmed the presence of the North Equatorial Counter Current (NECC), the Guinea Current (GC), and the South Equatorial Current (SEC). The report concludes that the region's oceanographic conditions are typical of the warm season, characterized by a deep oligotrophic surface layer, a strong pycnocline, and a subsurface chlorophyll maximum.

Keywords

Gulf of Guinea, Liberia, Marine Ecosystem, Physical Oceanography, Water Masses.

INTRODUCTION

The Gulf of Guinea is a large gulf of the Atlantic Ocean on the west coast of Africa. It is bordered by Liberia, Côte d'Ivoire, Ghana, Togo, Benin, Nigeria, Cameroon, Equatorial Guinea, and Gabon. Circulation patterns in this gulf are driven by major ocean currents, winds, and the region's unique bathymetry.

The most dominant surface current is the westward-flowing Guinea Current. This current circulates in a cyclonic gyre (counterclockwise), carrying warm tropical waters from the Gulf of Guinea across the Atlantic. The Guinea Current is strongest during the Northern Hemisphere summer when the Intertropical Convergence Zone moves northward [1].

Beneath the Guinea Current, flows the Guinea Counter Current eastward near the coast between about 4°N and 6°N latitude, forming part of the southern branch of the Atlantic subtropical gyre circulation. At deeper levels, the Gulf of Guinea is influenced by submarine currents such as the Intermediate Counter Current. Interactions between these currents, seafloor bathymetry, and wind regimes contribute to regional ocean circulation in the Gulf [1].

A key scientific question concerns the understanding of ocean mechanisms governing the evolution of water column temperature, salinity and mixed layer, as well as their variability on seasonal to interannual scales. The circulation in the Gulf of Guinea, for example, influences local marine ecosystems, fisheries and regional climate patterns. Thus, understanding and monitoring the variability of physical parameters and these dynamic current systems is essential for sustainable management of ocean resources.

As part of the agreement signed between the Ministerial Conference on Fisheries Cooperation among African States bordering the Atlantic Ocean (COMHAFAT), the National Institute of Fisheries Research of Morocco (INRH) and the National Fisheries and Aquaculture Authority of Liberia (NaFAA), a campaign to assess fish stocks and explore the marine ecosystem was carried out by INRH in the Liberian EEZ, aboard the research vessel Al Hassan Al Marrakchi between January 25 and February 29, 2024.

The objectives of this campaign were the assessment of abundance and biomass indices of the main pelagic and demersal exploited stocks of the Liberian continental shelf, the study of their biology, the survey of marine biodiversity and the study of the oceanographic state at the level of this maritime area. The campaign also saw the participation of local scientists from Liberia who brought their local experience on the marine environment and benefited from training on board the Al Hassan Al Marrakchi vessel.

MATERIALS AND METHODS

Survey Scope and Objective

As part of the cooperation of the Kingdom of Morocco and the Republic of Liberia, a sea survey was conducted in the Liberian EEZ onboard a Moroccan research vessel. The survey was intended to provide scientific information on the marine ecosystem components by carrying out various oceanographic research activities.

The survey thus provided an assessment of pelagic and demersal fish resources off Liberia and a state of the pelagic and benthic marine ecosystem on the continental shelf. The research activities at sea and the post analyzes on land was jointly supervised by scientists from Liberia and from the National Institute of Fisheries Research (INRH) of Morocco.

Multidisciplinary research activities on board the research vessel were planned in an ecosystem monitoring approach, considering the morphological and biological characteristics of the maritime continental shelf of the Republic of Liberia.

The survey targeted the continental shelf and part of the slope off Liberia on the depths extending from 15 - 20 to 500 meters (m). This area extends over approximately 5000 nautical miles square (nm^2), and its width varied between 12 and 24 nautical miles.

Oceanographic sampling

Oceanographic samples were taken in the same grid assigned to demersal trawling; i.e.33 sampling stations (***Fig. 1***). At each station, multiple types of sampling were carried out.

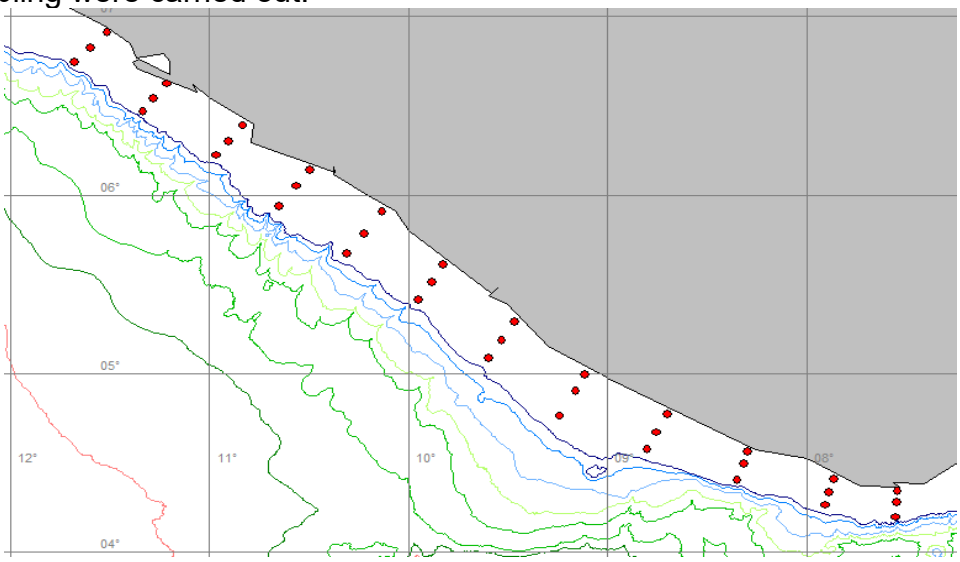

Fig. 1. Grid of the demersal trawling and the oceanographic sampling off Liberia

Physico-chimical sampling

Physico-chemical parameters data (temperature, salinity, oxygen, etc.) along the water column as well as water samples at different depth levels was carried out using the CTD carousel with 24 Niskin Bottles (***Fig. 2***). During the survey, a total

of 33 CTD profiles and 96 water samples for nutrient analysis were collected along the Liberian coast (***Fig.* 3**).

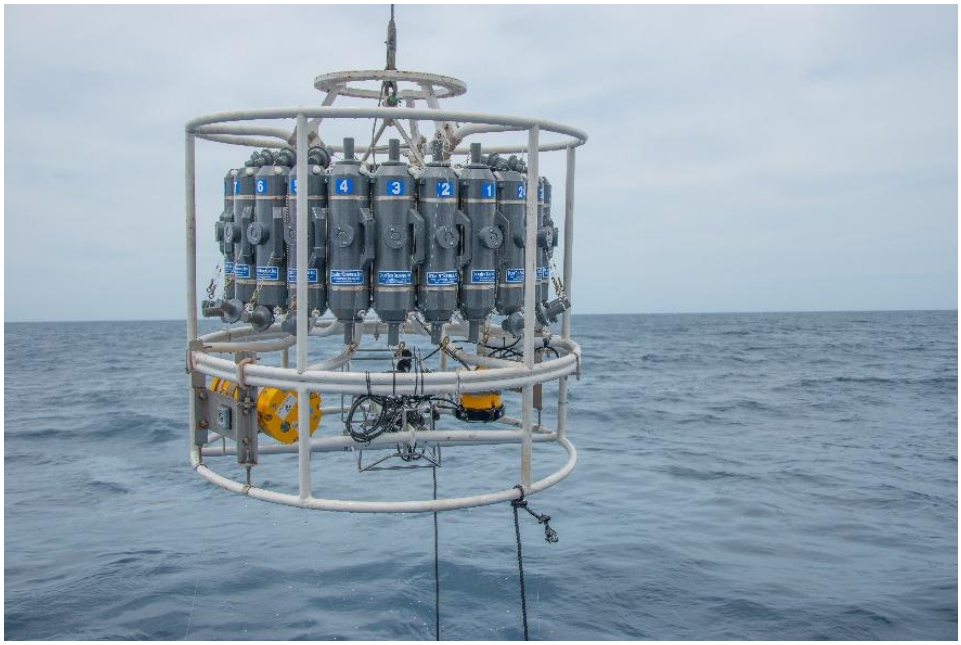

Fig. 2. The CTD Rosette



Fig 1. Network of CTD Stations where profiles were collected at different depths along the Liberian coast during the survey.

In parallel, the Thermosalinographe continuously recorded temperature and salinity data on the surface (***Fig.* 4**)



Fig. 4: Thermosalinographe system

Currents studies

The hull-mounted Acoustic Doppler Current Profiler (ADCP) was used to continuously record current data down to approximately 400 meters. For current requirements at deeper waters, the Lowered Acoustic Doppler Current Profiler (LADCP) system mounted on the CTD carousel was used at the oceanographic stations. A total of 9 LADCP profiles were collected along the Liberian coast (***Fig.***

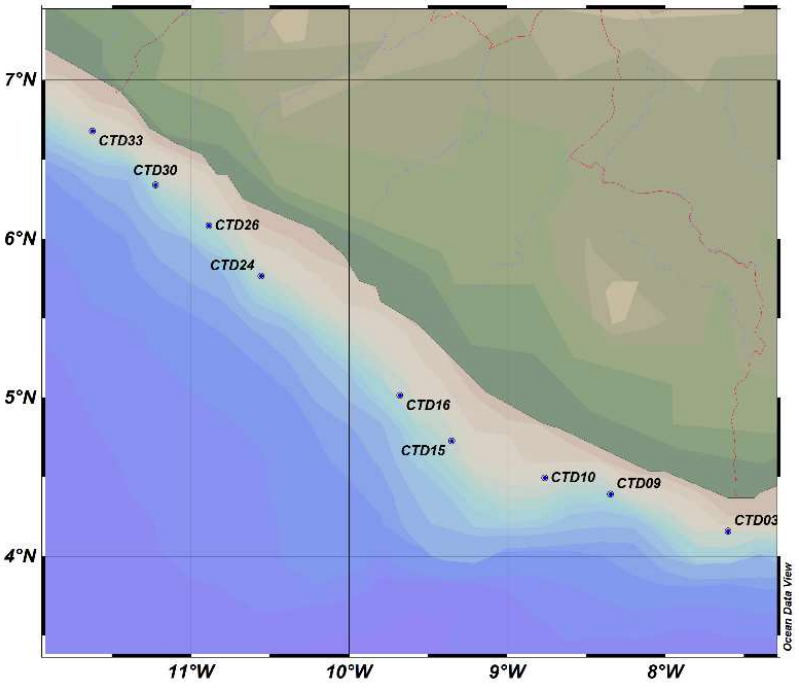

Fig. 2. LADCP station network

5).

Fluorescence sampling

Fluorescence data at the sea surface was also collected continuously during navigation by the fluorimeter system (***Fig.* 6**).



Fig. 6: Fluorimeter system

Data Analysis

All oceanographic data were subjected to quality control and filtering prior to analysis. CTD data were processed using Sea-Bird Scientific processing software, following the manufacturer's recommended procedures. This included sensor alignment, removal of spikes, elimination of pressure reversals, and application of thermal mass and conductivity corrections. A final visual inspection was performed to identify and exclude remaining outliers. Thermosalinograph and atmospheric parameters (e.g., wind speed and direction) were similarly filtered to remove erroneous values before further analysis. These quality-controlled datasets were used to ensure the reliability and reproducibility of the results.

Spatial and vertical analyses of oceanographic parameters were conducted using Ocean Data View (ODV). Horizontal distributions were analyzed through spatial maps and scatter plots, while vertical structures were examined using longitudinal sections (offshore and inshore), latitudinal sections, and vertical profiles. TS-diagrams were generated to identify water masses and mixing processes. Thermosalinograph data were visualized after filtering to assess surface variability, and atmospheric parameters were analyzed using graphical representations such as wind roses to characterize prevailing meteorological conditions during the survey.

Ocean circulation was investigated using Acoustic Doppler Current Profiler (ADCP) data processed with NCLIM software, enabling the derivation of current velocity profiles. Lowered ADCP (LADCP) data were processed following established methodologies that combine bottom-track measurements and inverse solutions to obtain full-depth current profiles. The processing approach is consistent with published methods (see: https://www.researchgate.net/publication/253711827_Deep_Velocity_Profiling_Using_Lowered_Acoustic_Doppler_Current_Profilers_Bottom_Track_and_Inverse_Solutions).

RESULTS

Oceanographic parameters

1. Spatial distributions

The spatial distribution of sea surface temperature varies between 29.6°C and 30.8°C, with an east-west gradient. The lowest temperatures, between 29.6°C and 30°C, are found in the part between 11°W and 12°W, while the warmest, reaching 30.8°C, are found offshore, between 10°W and 7°W. At 25 meters depth, a colder temperature is observed, around 20°C near the coast, while the warmest waters are located offshore. At 50 meters depth, the minimum temperature is around 18°C, and the highest temperature in this layer is around 20°C offshore. In subsurface waters, a remarkable decrease in temperature of about 3°C is observed for every 100 meters of depth, with 16°C at 100 meters, 13°C at 200 meters and 10.4°C at 300 meters of depth. The distribution of surface salinity shows a large difference between the coast and the open sea due to the freshwater input from rivers. The minimum salinity is observed near the coast, about 33 PSU, and a salinity of about 34 PSU offshore. At 25 meters depth, a significant increase in salinity is observed, of the order of 36 PSU in the east and 35 PSU in the west. At 50 meters depth, the salinity is almost homogeneous, with a value of about 35.9 PSU in the eastern part. In subsurface waters, a decrease in salinity is observed as a function of depth, varying from 35.7 PSU at 100 meters to 35 PSU at 300 meters depth, (***Fig.7***).

The distribution of dissolved oxygen in the region varies between 3.1 ml/l and 2.9 ml/l. The maximum concentration, exceeding 3.4 ml/l, was detected at a depth of 25 meters, just above the maximum fluorescence concentration observed at 35 meters depth, (***Fig.* 8).**

To better understand the relationship between dissolved oxygen concentration and fluorescence concentration (indicator of phytoplankton biomass), a series of point clouds were made in (***Fig.* 9 and 10)**. The (***Fig.* 11)** shows that the depth where the maximums of these two parameters are located is in the layer between 20 and 60 meters. The salinity favorable to biological production varies between 35.2 PSU and 35.9 PSU, while the temperature range favorable to biological productivity is between 18 ° C and 25 ° C.

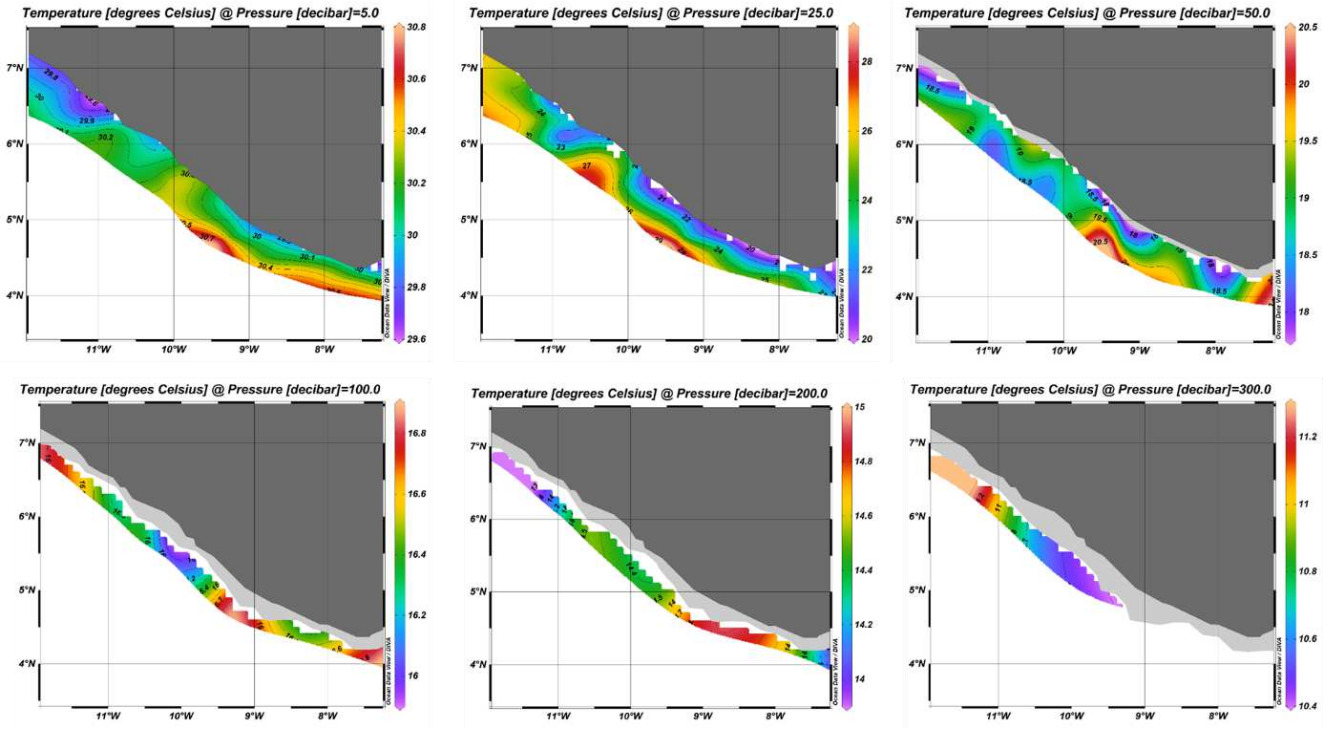

Fig. 7. Spatial distributions of surface temperature up to 300m depth

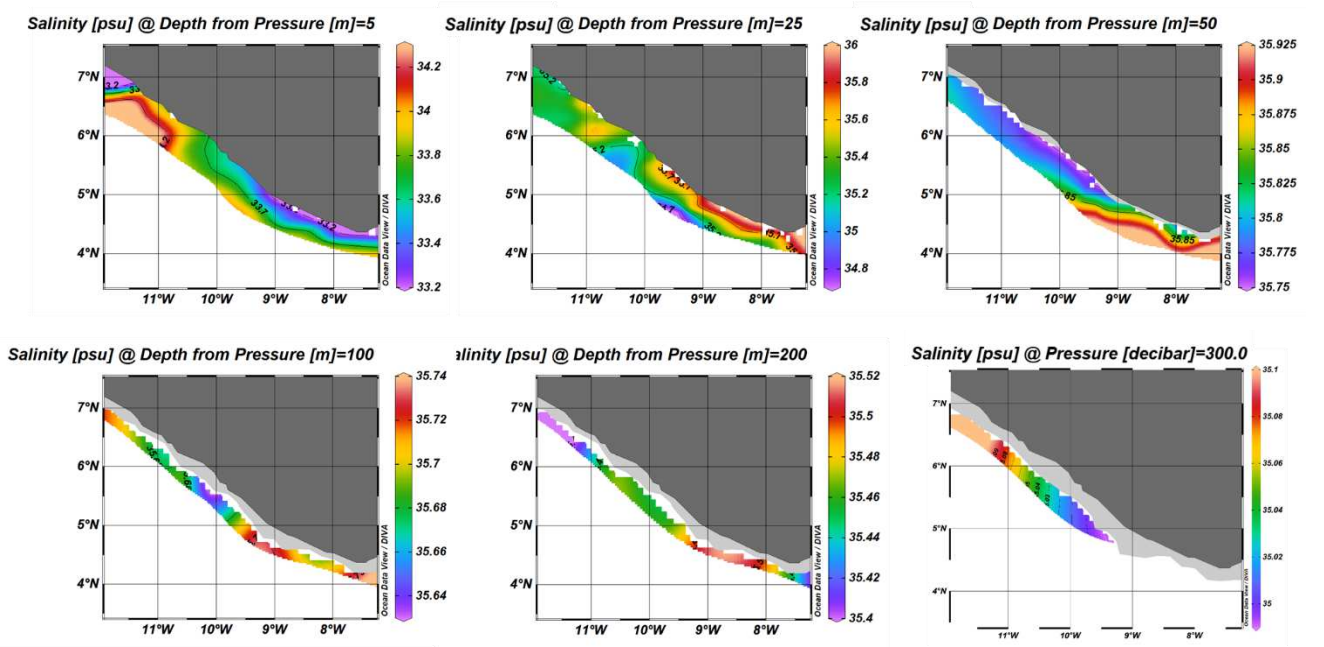

Fig. 8: Spatial distributions of salinity from the surface to 300m depth

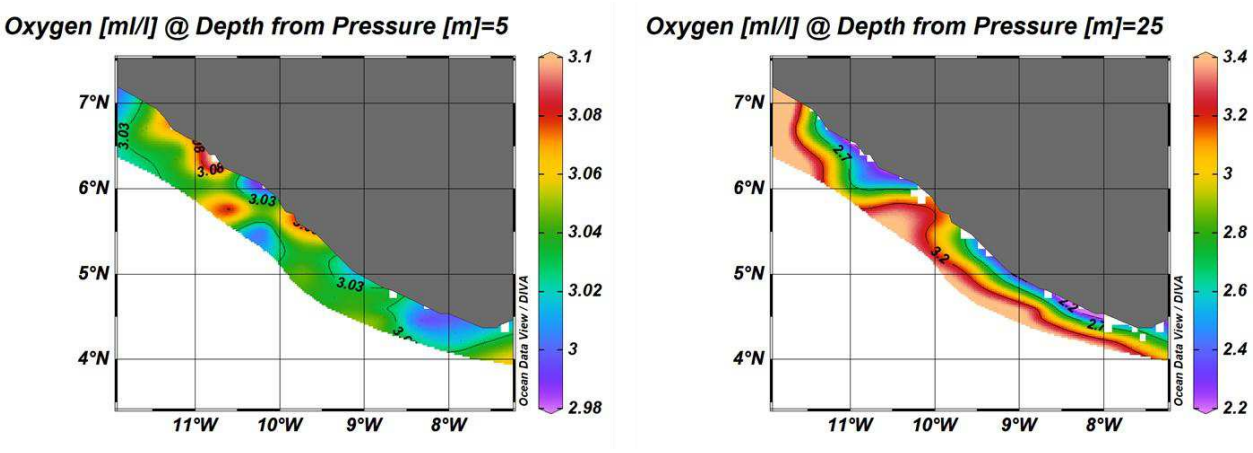

Fig. 9: Spatial distributions of oxygen at 5m and 25m depth

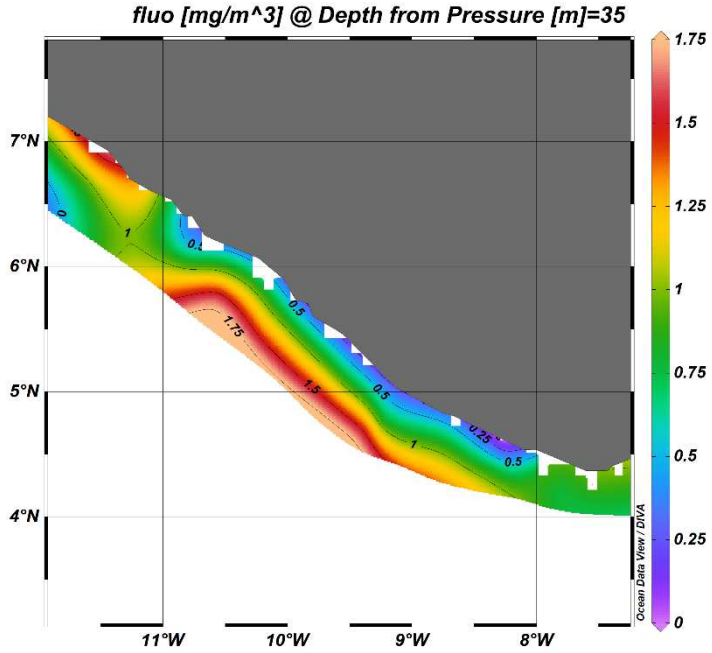

Fig. 10: Spatial distributions of fluorescence (mg/m3) at 35m depth

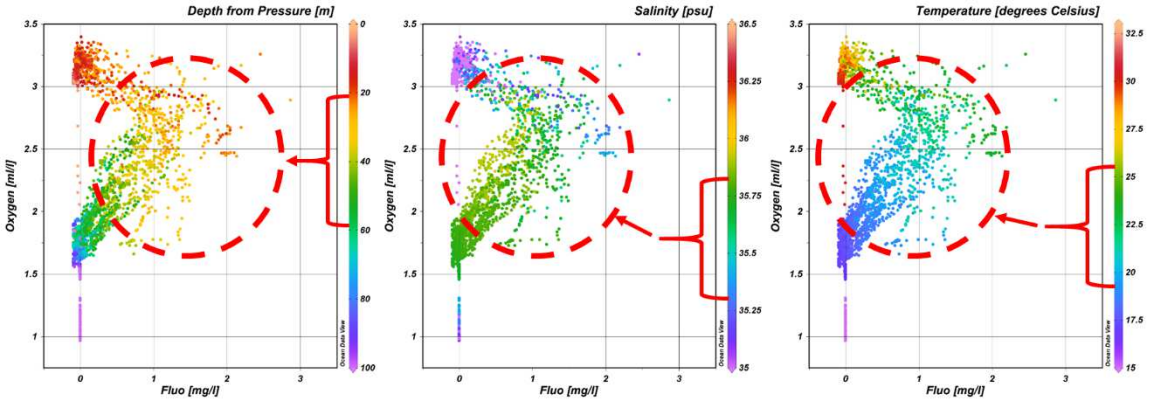

Fig. 3: Maximum fluorescence as a function of oxygen, temperature, salinity and depth.

2. *Vertical distributions*

This part deals with the vertical distributions of oceanographic parameters off Liberia, in order to better understand and visualize their changes as a function of depth and east-west direction.

a) Longitudinal section offshore

The offshore section (***Fig.* 12**). The vertical distribution of fluorescence off Liberia shows that the maximum concentration is between 20 and 60 meters depth, (***Fig.* 13**).

The distribution of dissolved oxygen shows a maximum concentration at the surface due to chemical exchanges between the ocean and the atmosphere. A high concentration is also found between 20 and 45 meters deep. This concentration decreases with depth until reaching approximately 1 ml/l, (***Fig.* 14**).

The vertical distribution of salinity shows a gradient between the surface and the bottom. The minimum salinity values, of the order of 33 PSU, are found at the surface, which can be explained by the freshwater inputs from rivers along the Liberian coast. Below this surface layer, an increase in salinity is observed reaching 35.75 PSU. Below this intermediate layer, a decrease in salinity is observed between 34.6 and 35 PSU, (***Fig.* 15**).

The vertical temperature distribution shows a stratification of the water column, with a maximum surface temperature of about 30°C. This temperature decreases rapidly with depth, where a temperature of about 20°C is found at 40 meters, 15°C at 160 meters, and 10°C at 300 meters depth. This strong temperature gradient characterizes the hot season in the Gulf of Guinea, (***Fig.* 16).**

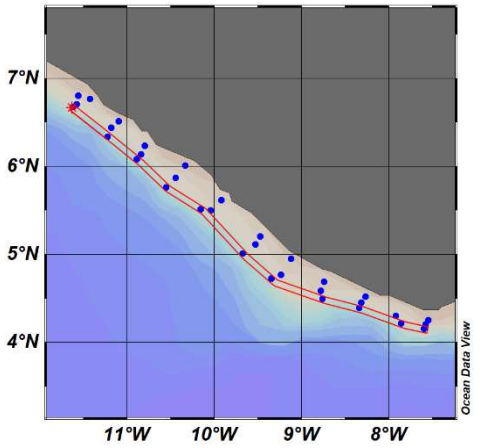

Fig. 12: Oceanographic section of the open sea

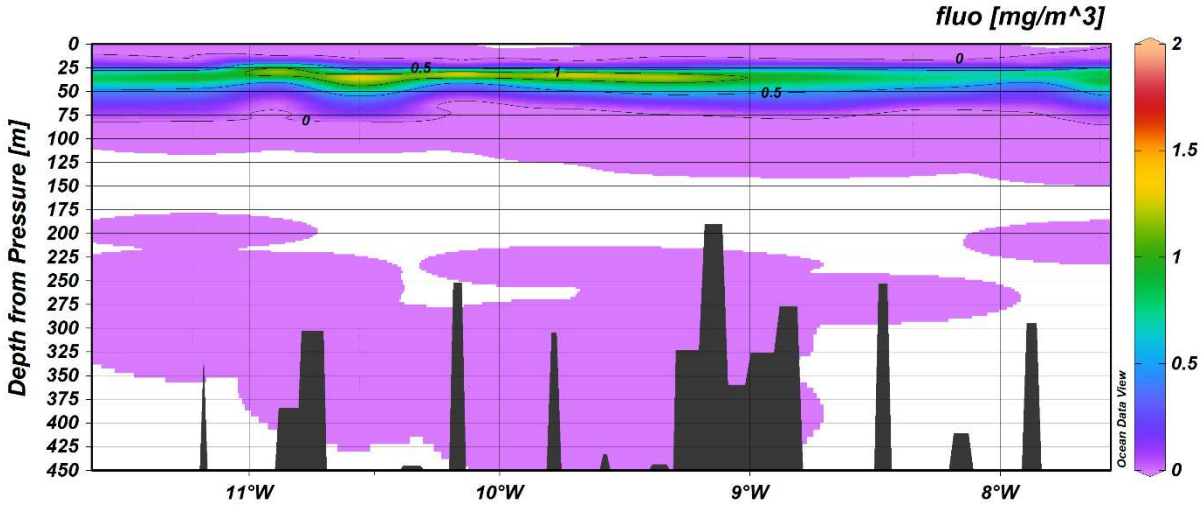

Fig. 13: Vertical section of fluorescence concentration

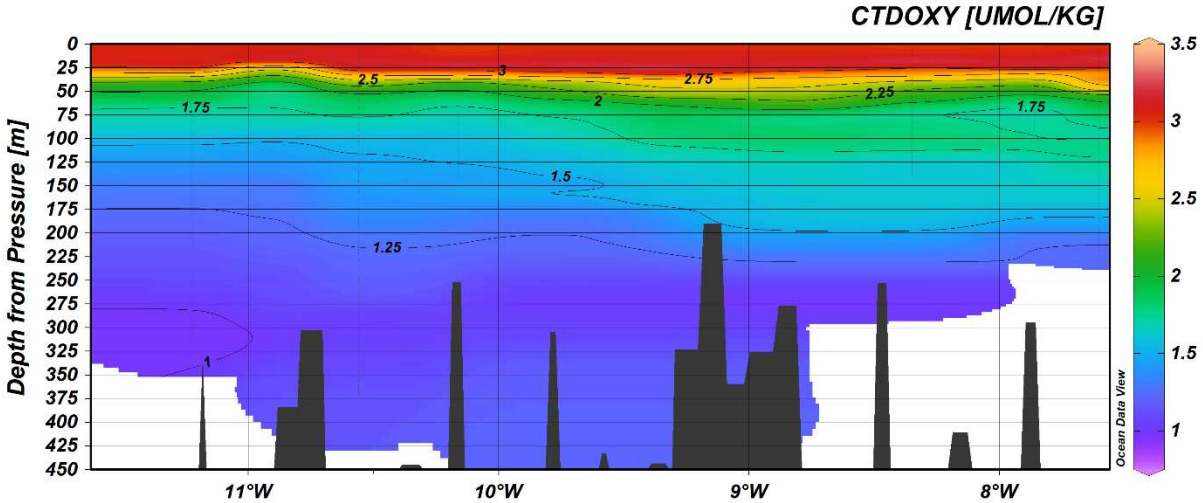

Fig. 14: Vertical section of oxygen concentration

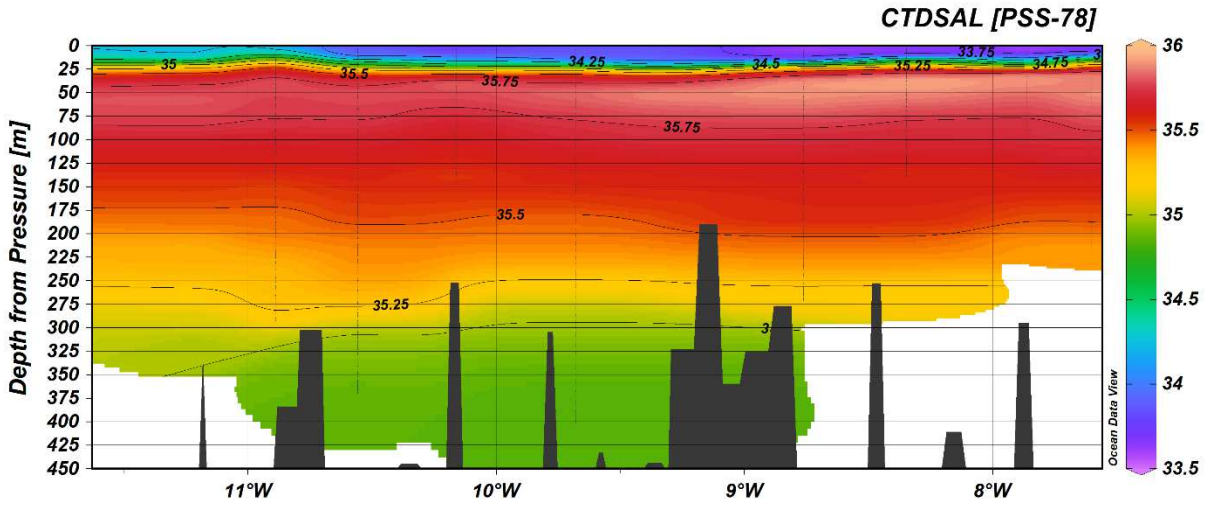

Fig. 15: Vertical section of salinity

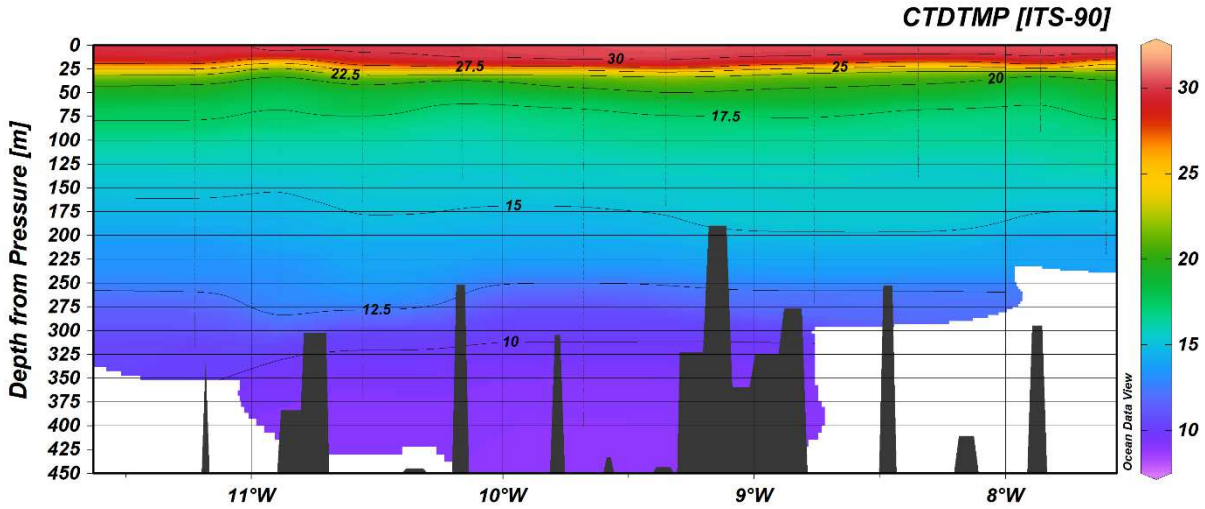

Fig. 16: Vertical section of the temperature

b) Longitudinal section inshore

The distribution of vertical section of fluorescence along the coast reveals a disparity between the east and the west (***Fig.*** **17**)., with a more marked concentration of fluorescence to the west of Liberia, (***Fig.*** **18**). Similarly, the distribution of oxygen shows a high concentration at the surface, which decreases with depth, (***Fig.*** **19**). Salinity shows a range of values varying from 33 PSU to 36 PSU, with a notable difference between the east and the west, (***Fig.*** **20**). This disparity is also confirmed in the vertical distribution of temperature, where a temperature range of 30°C is observed at 22.5°C in the west, and a more pronounced gradient in the eastern part, where the temperature varies from 30°C to 17°C between the surface and 75 meters deep, (***Fig.*** **21**).

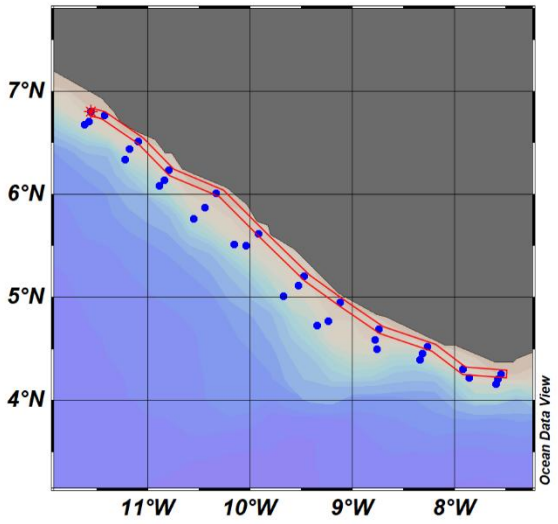

Fig. 17: Coastal oceanographic section

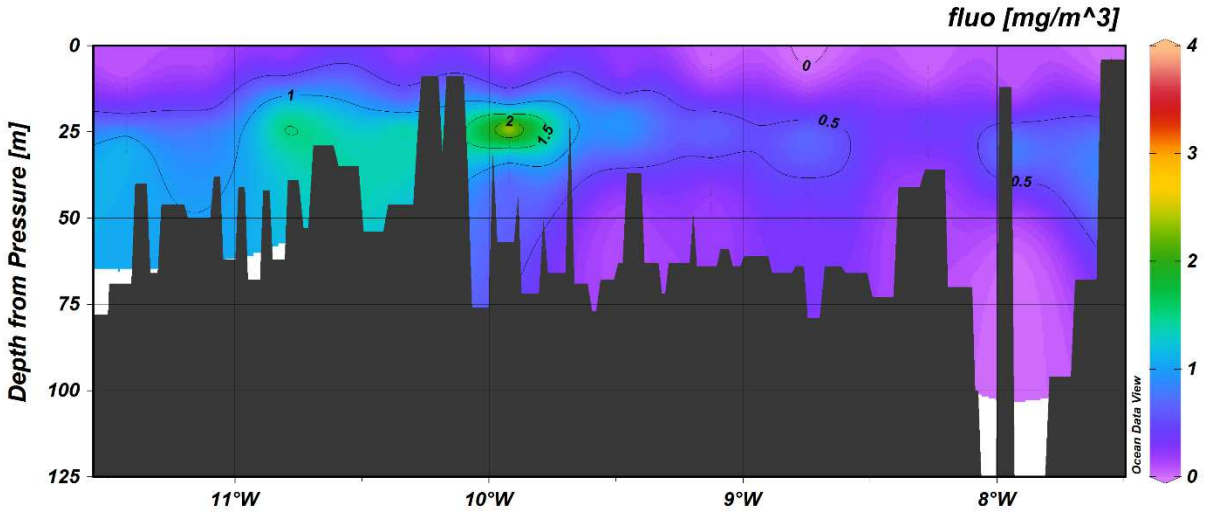

Fig. 18: Vertical section of fluorescence

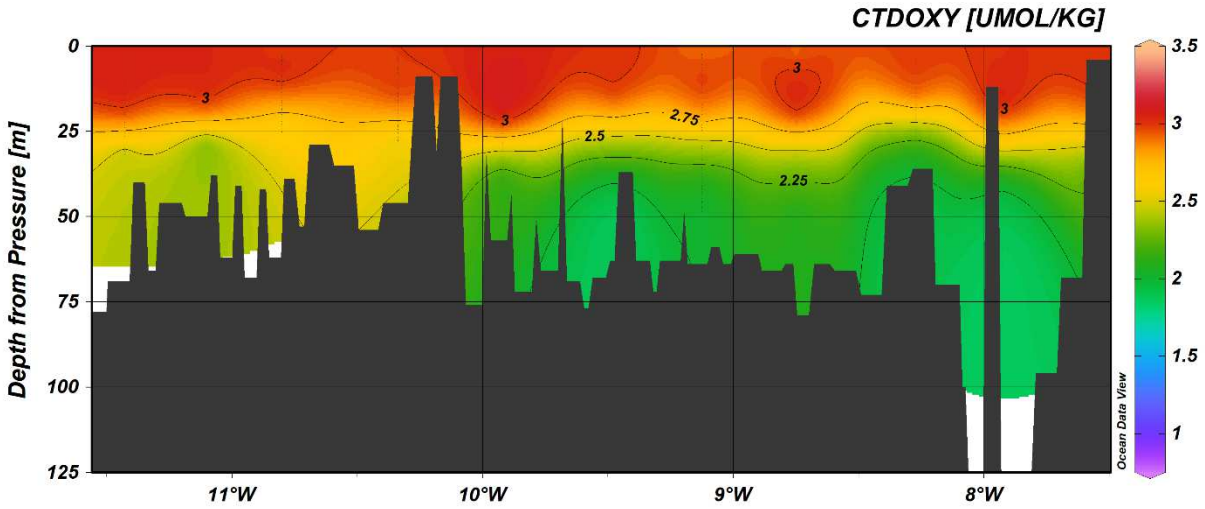

Fig. 19: Vertical section of oxygen

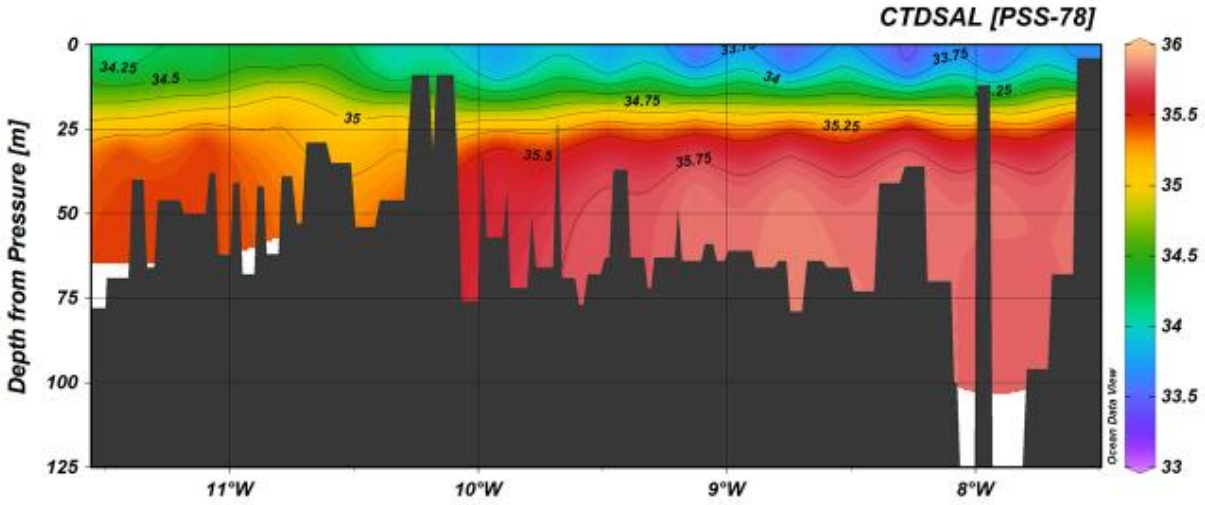

Fig. 20: Vertical section of salinity

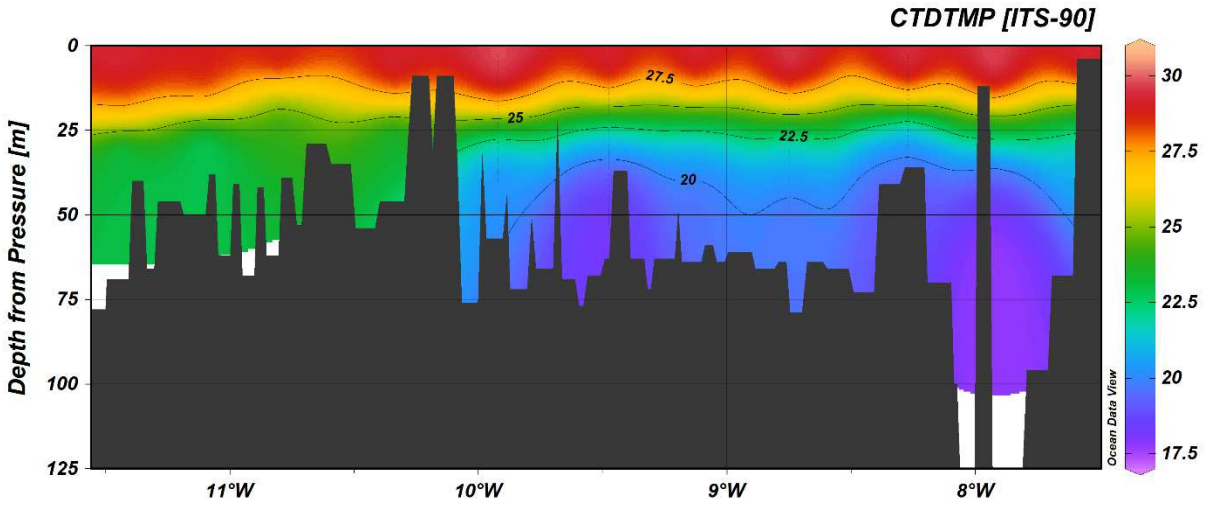

Fig. 21: Vertical section of the temperature

c) Latitudinal section

***Fig.* 22** illustrates the coastal-offshore section. This vertical distribution allows us to better understand the variations in physical parameters between the coast and the open sea as a function of depth.

The vertical distribution of temperature between the coast and the open sea reveals a strong thermal gradient, with warm surface waters of around 30°C and cold deep waters around 7°C. This marked thermal stratification of the water column indicates the presence of a thermocline, a very stable layer that prevents vertical mixing and exchanges between surface water masses and deep water masses (***Fig.* 23**).

At the same time, the vertical salinity profile also shows a contrasting structure. At the surface, the slightly saline waters around 33 PSU indicate freshwater inputs. Then the salinity increases rapidly to maximum values of 35.5 PSU between 50 and 250 m depth. Below this, it decreases slightly to reach 35 PSU in the deep seabed. This distribution reflects the superposition of water masses with different salinity characteristics on the vertical, (***Fig.* 24**).

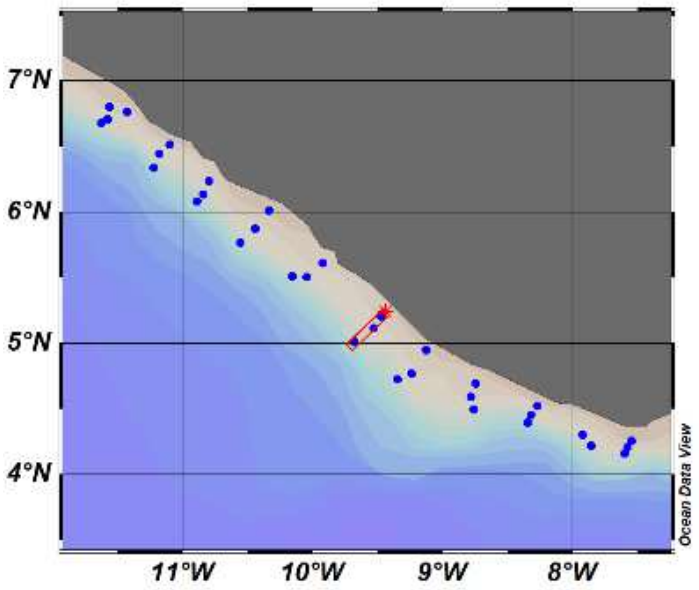

Fig. 22: Coast-offshore oceanographic section

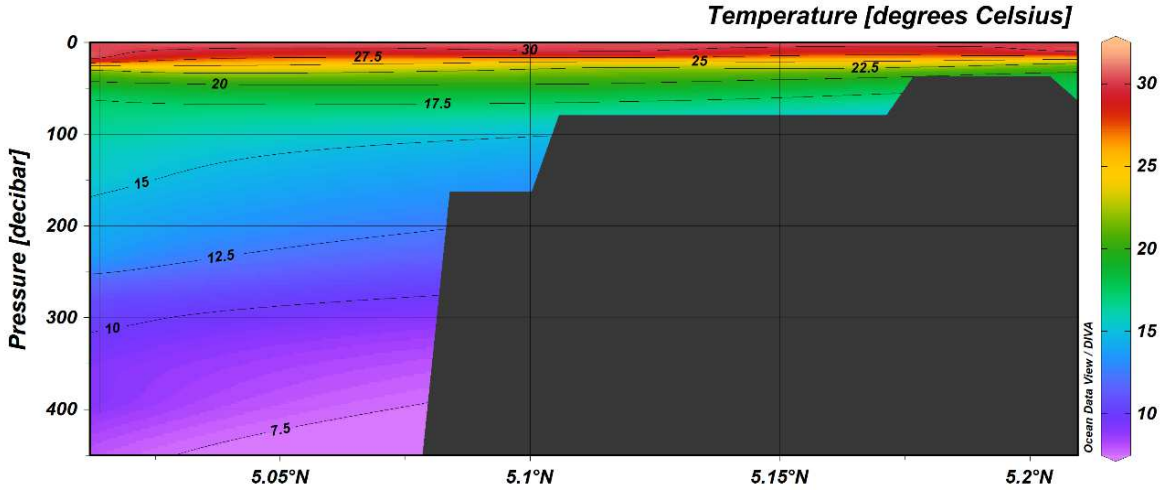

Fig. 23: Coast-wide section of temperature

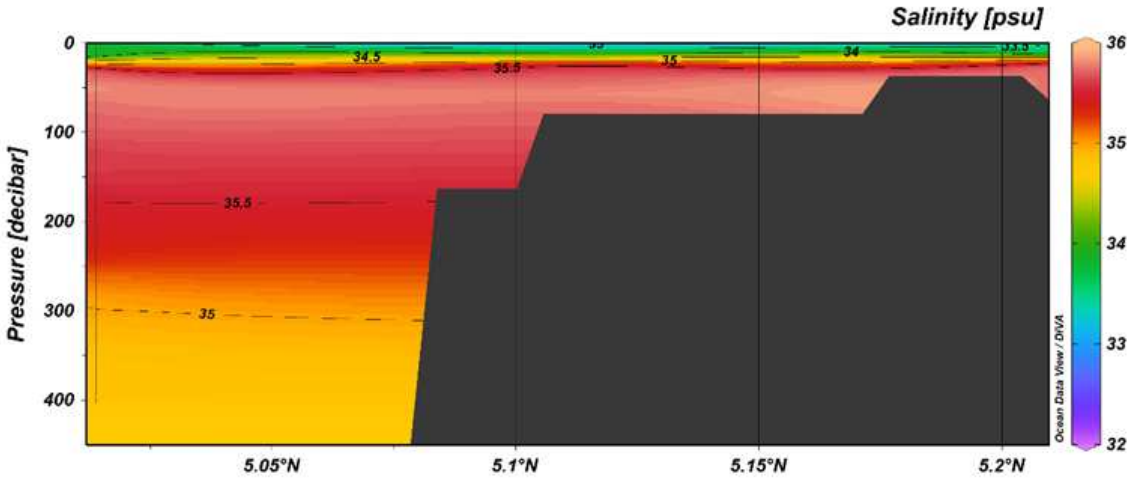

Fig. 24: Coast-to-sea section of salinity

3. TS diagram

The TS (Temperature-Salinity) diagram is a graphical tool that allows to simultaneously represent four key parameters: temperature, salinity, density and depth. This synthetic representation is particularly useful to identify and characterize the different water masses present. This vertical stratification of the Thermohaline properties reflects different origins for each of these water masses, allowing their identification on the TS diagram.

In the TS diagram (***Fig.* 25**), three main water masses can be distinguished, each characterized by specific properties of temperature, salinity and density [2, 3]:

- Tropical Surface Water (TSW),
- Subtropical Underwater (STUW),
- South Atlantic Central Water (SACW),

Table 1. Properties of observed water masses

Body of water		**Temperature (°C)**	**Salinity (PSU)**	**Density $\sigma\,\theta$**
TSW	The range	20.4–26.1	32.9–34.6	Surface – 26.2
STUW	The range	13.0–16.5	34.7–35.0	25–25.5
SACW	The range	9.7–17.4	35.0–35.8	26.2–27.05

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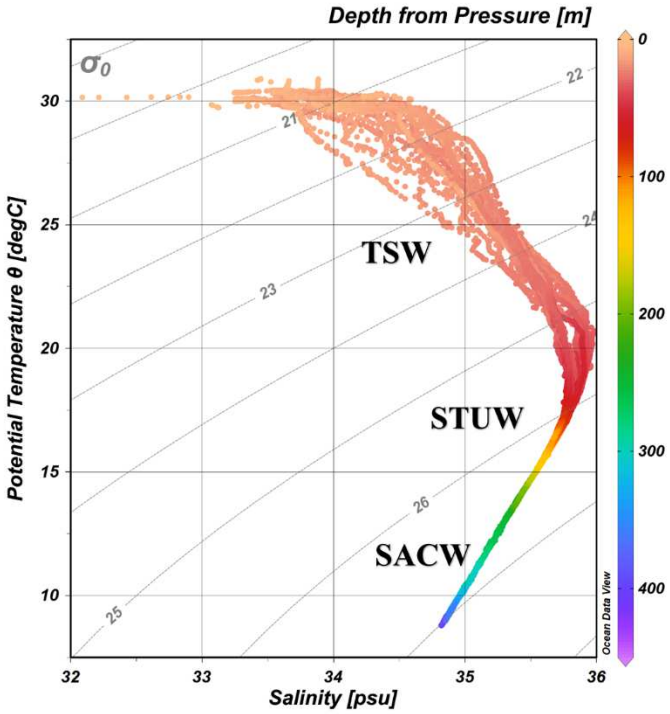

Fig. 25: TS diagram

4. Thermosalinograph

In order to obtain a better spatial resolution of surface temperature and salinity distributions, a thermosalinograph was deployed during this oceanographic campaign (***Fig.*** **26**).

Data collected by this instrument indicate a remarkable homogeneity of surface temperature along the coast of Liberia, with values ranging from a maximum of 31°C to a minimum of about 30°C. In contrast, a pronounced coastal-offshore gradient is observed for surface salinity. Offshore waters have the highest salinities, reaching 33.5 PSU, while minimum salinities, of the order of 32 PSU, are encountered near the coast. This decrease towards the coast reflects the influence of freshwater inputs from rivers flowing into this region (***Fig.*** **27**).

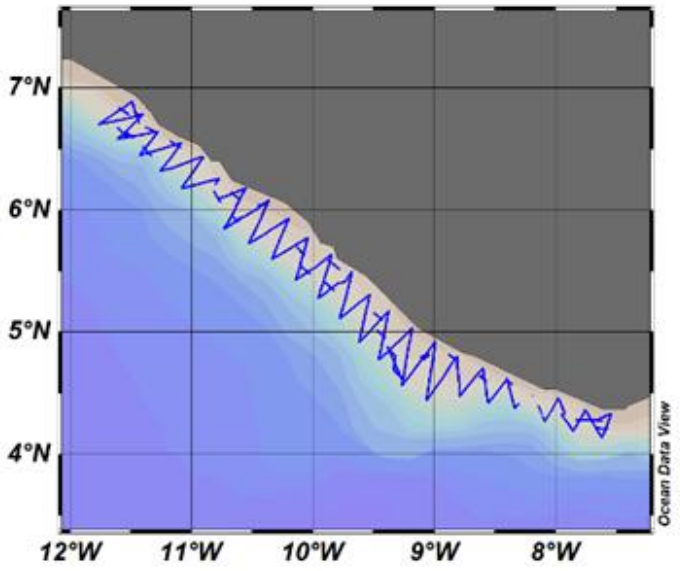

Fig. 26. Thermosaelinograph measurement path

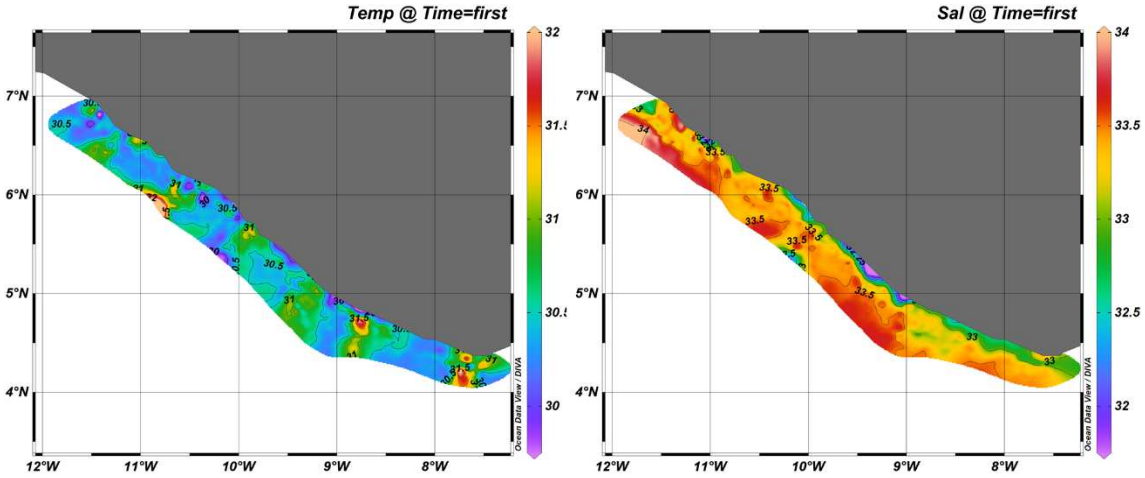

Fig. 4: Surface distributions of temperature (left) and salinity (right)

Weather parameters

The eastern region of the tropical Atlantic Ocean is subject to a trade wind regime whose seasonal variations fundamentally condition those of the ocean [2]. In the eastern part of the basin, east of 20°W, the dominant trade winds vary from south to southeast and east to south of the equator and become southwest along the coasts of the GG, thus generating a monsoon phenomenon during the boreal summer, called the African monsoon. Although the seasonal variations in atmospheric flow are relatively weak compared to those observed in the west of the basin, they are nevertheless characterized by a clear strengthening of wind

intensity during the boreal summer, in relation to the northward shift in latitude of the Saint Helena anticyclone [4], (***Fig.* 28**).

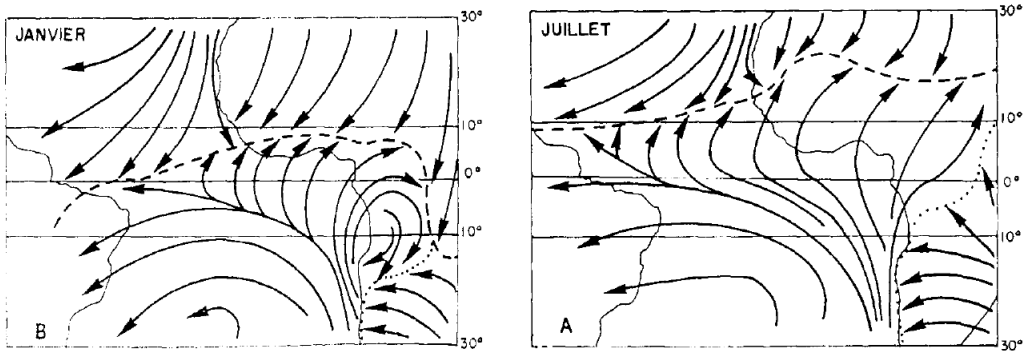

Fig. 28: Mean surface atmospheric circulation pattern in the equatorial Atlantic and the Gulf of Guinea, for the months of January (left) and July (right). The meteorological discontinuities represented are the meteorological equator (dashed) and the interoceanic confluence (dotted).

The meteorological data collected indicate that the prevailing winds in this region generally blew from the southwest, with average speeds between 2 and 6 m/s, as illustrated by the wind rose (***Fig.* 29**).

As for atmospheric parameters, the air temperature ranged from 26°C to 32°C. The atmospheric pressure varied from 1008 hPa to 1015 hPa over the area and period considered. Finally, the relative humidity values were high, ranging from 65% to 98% (***Fig.* 30**).

These weather conditions, with warm temperatures, high humidity and moderate southwesterly winds, are characteristic of the monsoon regime of this coastal region during this period (***Fig.* 31**).

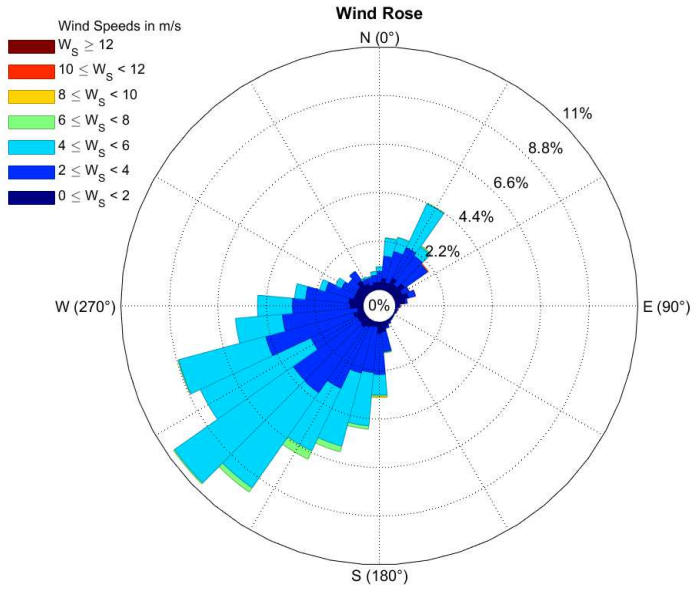

Fig. 29: Wind rose showing the main currents that characterize the Gulf of Guinea

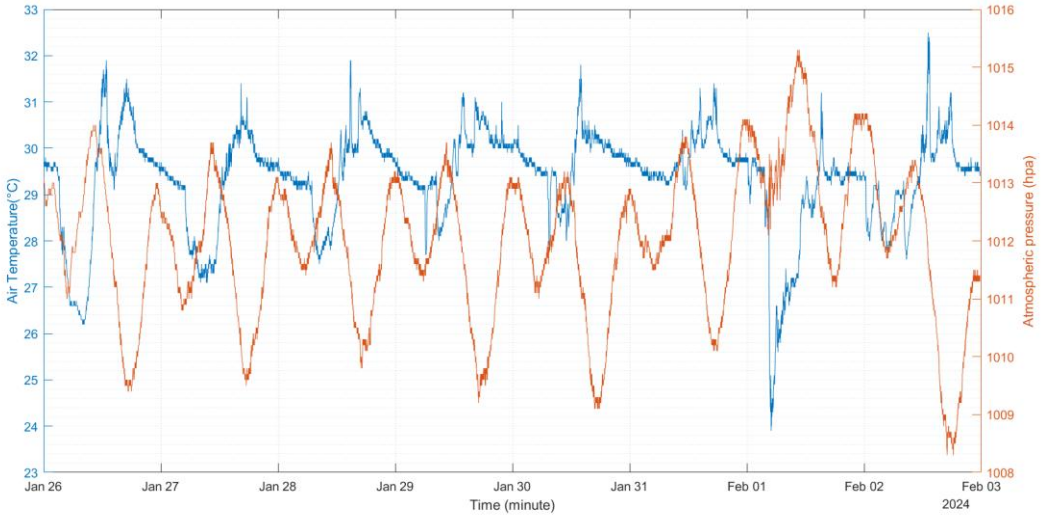

Fig. 30: Variations in air temperature and atmospheric pressure

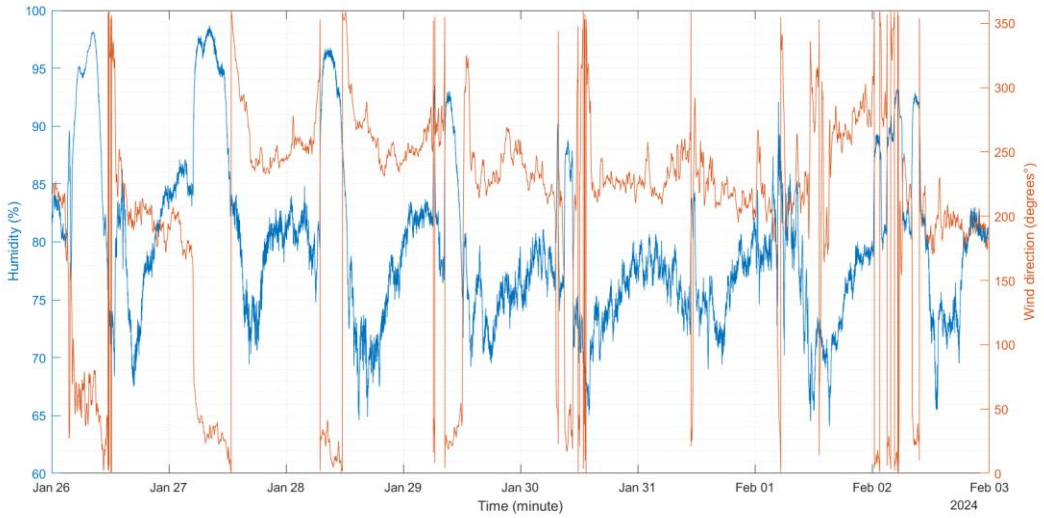

Fig. 31: Variations in wind direction and humidity

Ocean Circulation

The Liberian coast is characterized by a complex circulation, influenced by several factors such as winds, ocean currents, tides, as well as variations in temperature and salinity. The ocean circulation in the Gulf of Guinea has several important components: The Guinea Current: It moves along the West African coast towards the east. The Equatorial Current: It runs from east to west off the coast and is part of the global thermohaline circulation. Seasonal variations in currents: They are influenced by winds and precipitation. ***Fig.* 32** shows the main currents characterizing the Gulf of Guinea [2].

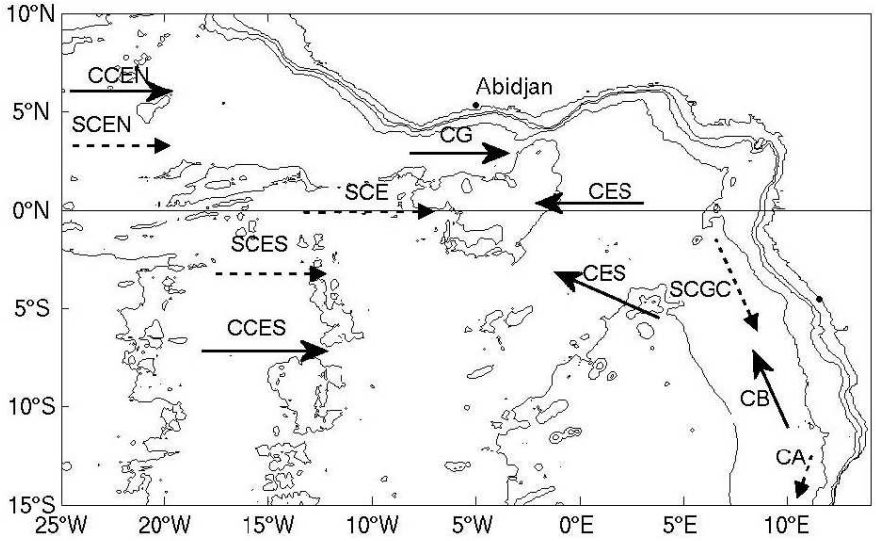

Fig. 32: subsurface circulation scheme in the eastern equatorial Atlantic and the Gulf of Guinea. Surface currents (solid arrows): North Equatorial Counter Current (NECC); Guinea Current (GC); South Equatorial Counter Current

(SEC); South Equatorial Current (SEC); Benguela Current (BC). Subsurface currents (dashed arrows): North Equatorial Undercurrent (NEUC); Equatorial Undercurrent (EUC); South Equatorial Undercurrent (SEC); Gabon-Congo Undercurrent (GCUC); Angola Current (AC). (Bourles and Caniaux , 2004)

During the campaign, the ADCP (Acoustic Doppler Current Profiler) was used to continuously measure the ocean circulation along the Liberian coast, from the surface to about 400m depth . The surface ocean circulation (16 to 24 meters) is characterized by a dominant southeasterly direction, with high velocities in the western and eastern parts, while the current speed is low in the center, (***Fig.* 33**).
Between 32 and 40 meters depth, the same direction of the south-east current is observed in the west, but a reversal of direction towards the north-west with a speed of about 30 cm/s in the eastern part, (***Fig.* 34**). Between 48 and 56 meters depth, the speed of the ocean circulation decreases in the western part, while the eastern part experiences an increase reaching 40 cm/s, (***Fig.* 35**).
Between 104 and 112 meters depth, the northwest direction persists in the east with a speed of about 30 cm/s, (***Fig.* 36**). At 250 meters depth, the southeast direction becomes dominant again in the majority of the region studied, (***Fig.* 37**).
At around 300 meters depth, a decrease in the northwest current is observed in the eastern part of Liberia, (***Fig.* 38**). At 370 meters depth, the speed of the currents is low, less than 15 cm/s, with a general southeast direction, (***Fig.* 39**).

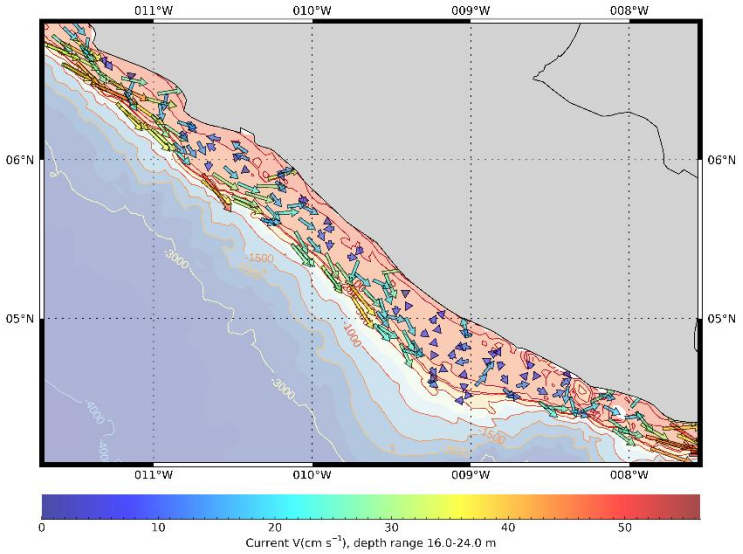

Fig. 33: Distributions of ocean circulation between 16-24 m

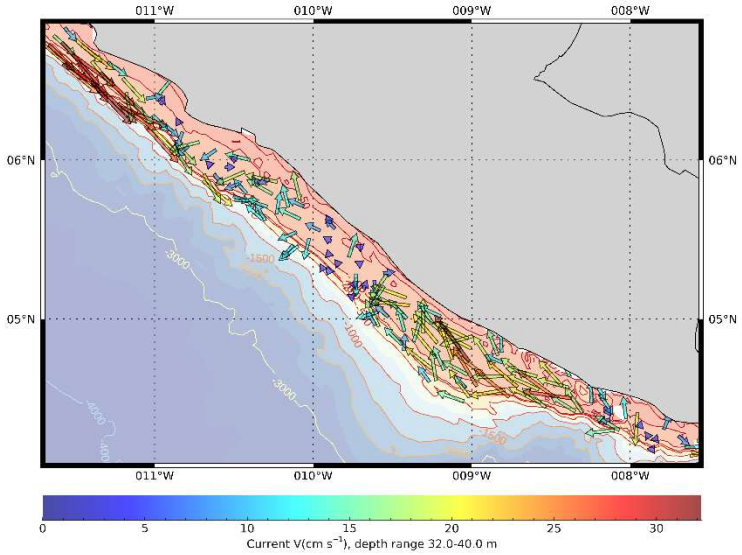

Fig. 34: Distributions of ocean circulation between 32-40 m

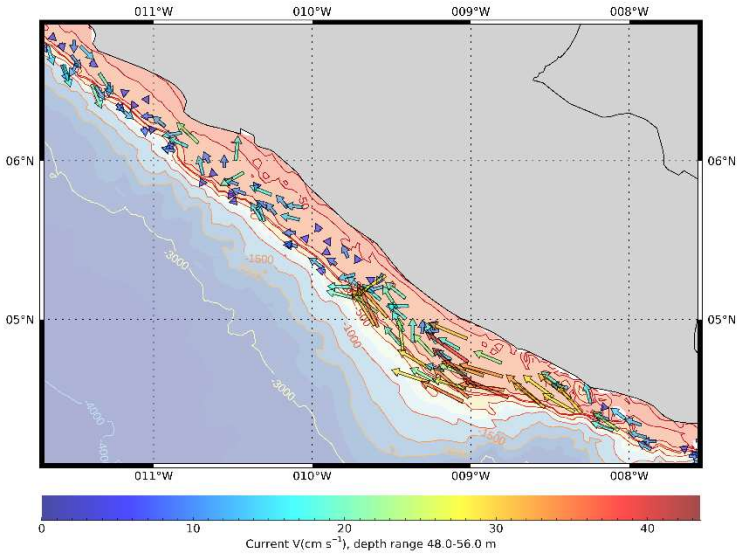

Fig. 5: Distributions of ocean circulation between 48-56 m

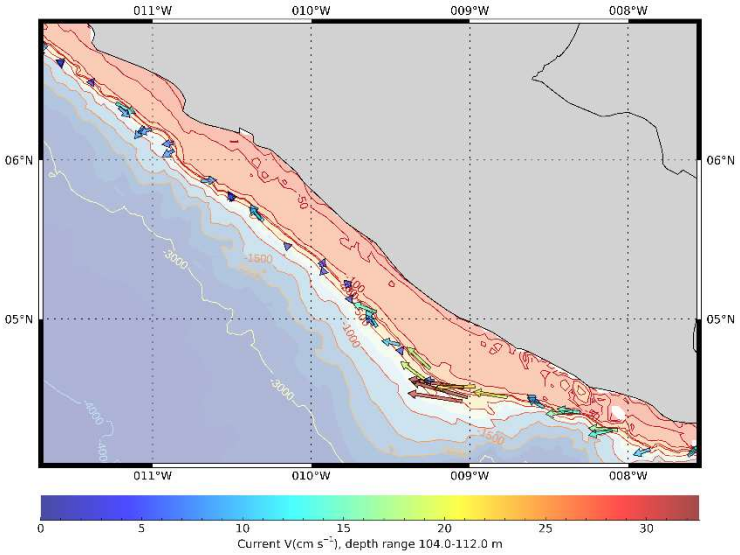

Fig. 36: Distributions of ocean circulation between 104-112 m

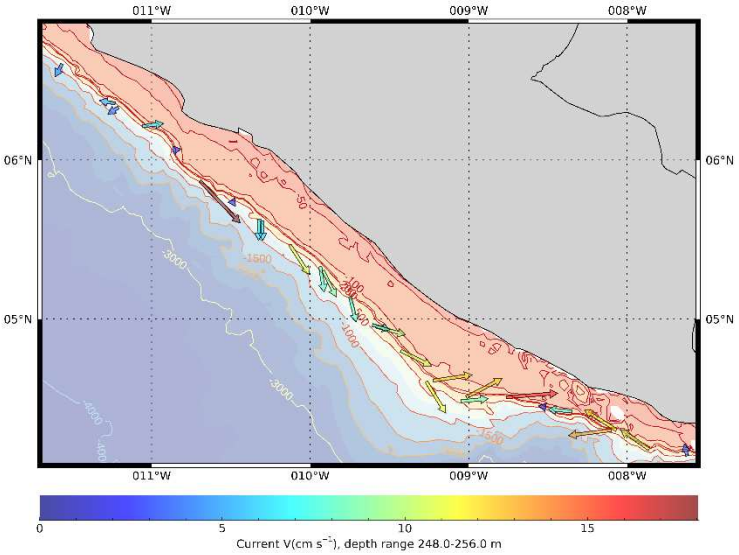

Fig. 37: Distributions of ocean circulation between 248-256 m

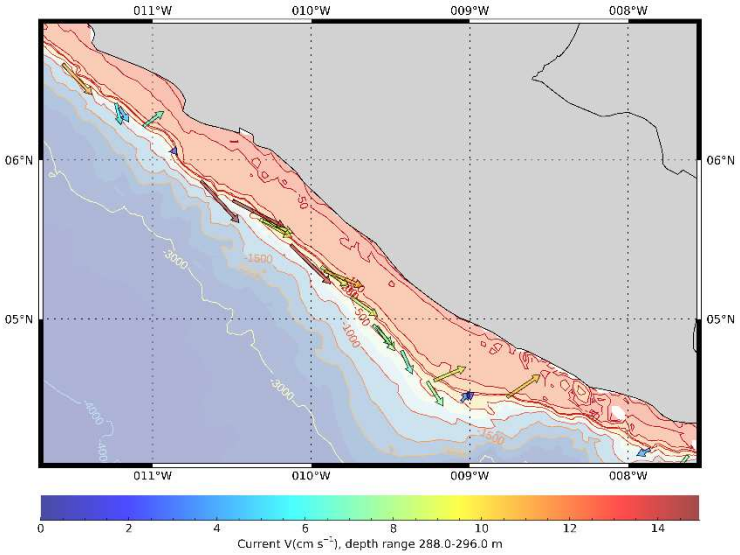

Fig. 38: Distributions of ocean circulation between 288-296 m

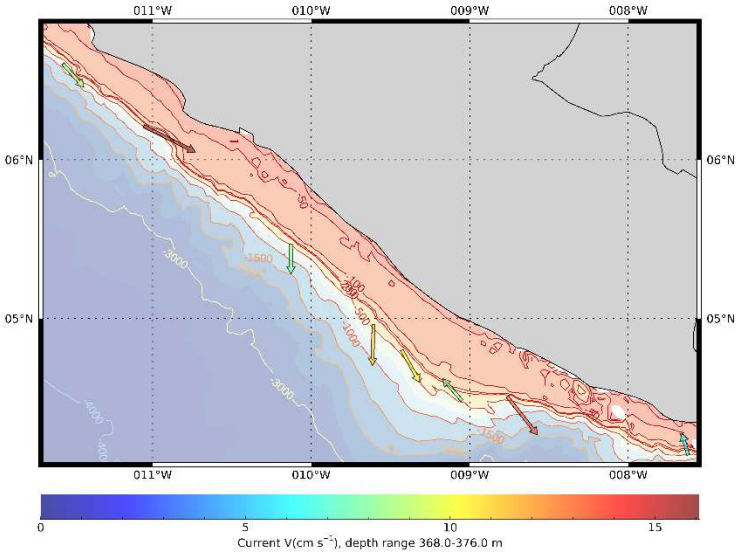

Fig. 39: Distributions of ocean circulation between 368-376 m

The second instrument to measure ocean circulation was LADCP (Lowered Acoustic Doppler Current Profiler), this instrument was used in parallel with the CTD stations to measure ocean circulation throughout the water column. In this section, we will focus on the results from station 03, representative of the eastern part, and station 30, representative of the western part. At station 03, the direction of the currents is predominantly southeast throughout most of the water column, with a maximum surface speed that decreases with depth. At station 30, we observe a change in the speed and direction of ocean currents as a function of depth. On the surface, the speed of the currents is low. From 50 meters deep, the direction becomes northwest. From 100 meters

deep, this direction reverses and becomes southeast. At 300 meters deep, we observe a low speed of the currents, (***Fig.*** **40**).

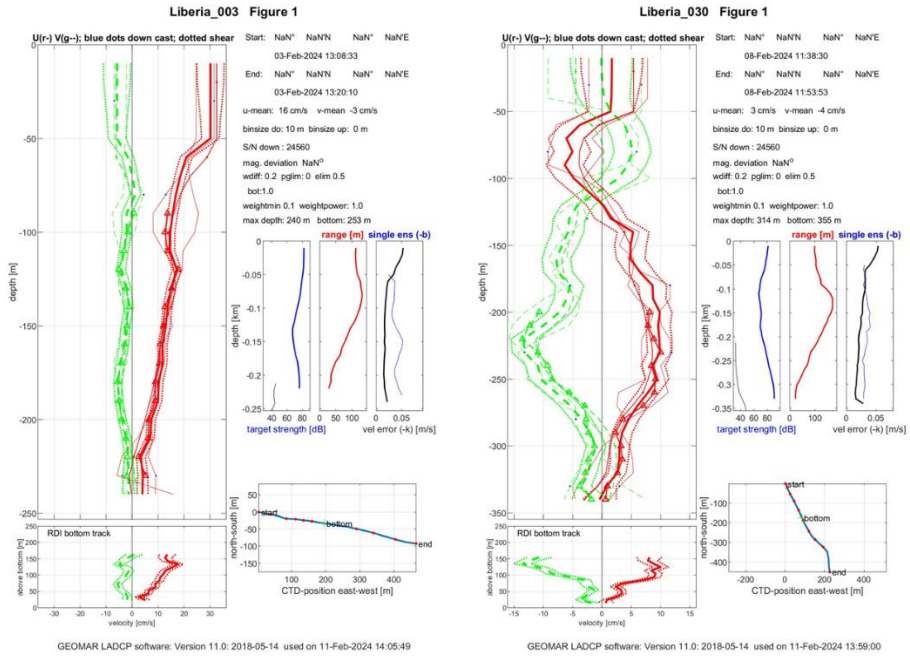

Fig. 40: LADCP profiles of stations 03 and 30

The results of the ocean circulation distribution data collected during this cruise using the ADCP and LADCP allowed the detection of the North Equatorial Counter Current (NECC), the Guinea Current (CG) and the South Equatorial Current (SEC), as illustrated in ***Fig.*** **41** [5].

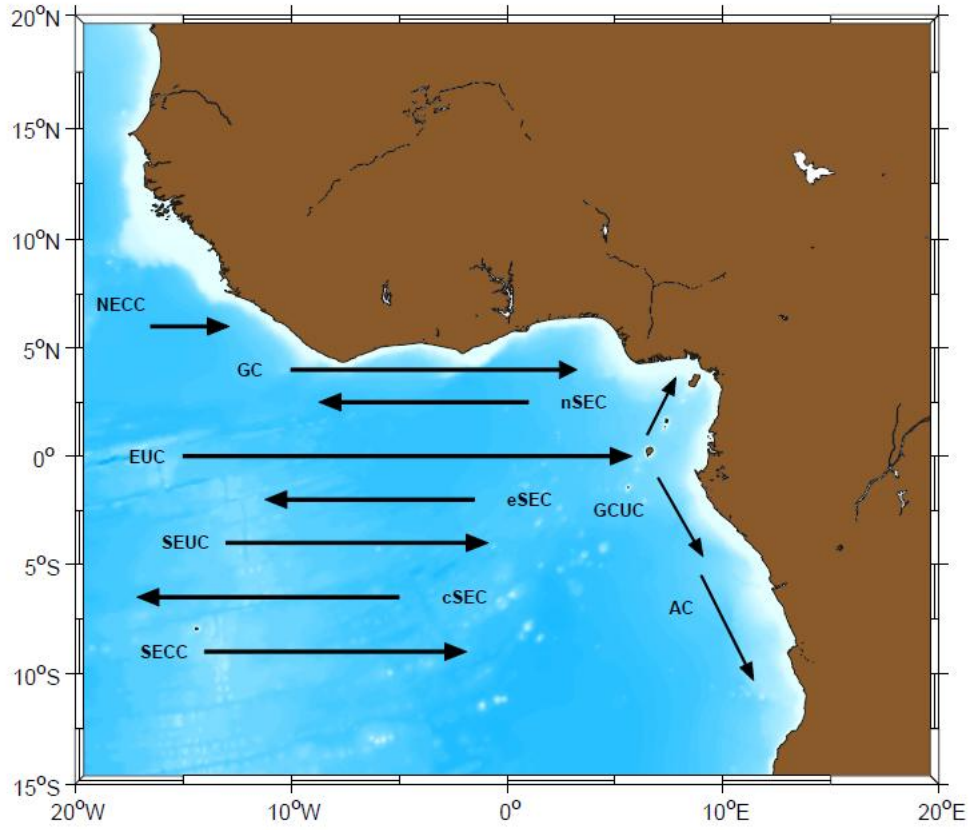

Fig. 41: Schematic map showing the horizontal distribution of the major eastern tropical currents. Shown are the North Equatorial Countercurrent (NECC), the Guinea Current (GC), the South Equatorial Current (SEC) with the northern (nSEC) and equatorial branches (eSEC), the Equatorial Undercurrent (EUC), the Gabon-Congo Undercurrent (GCUC), the Angola Current (AC), the South Equatorial Undercurrent and the South Equatorial Countercurrent (SECC), (Fischer, 2008).

DISCUSSION AND CONCLUSION

The Gulf of Guinea region experiences notable variations in ocean surface temperature. These thermal anomalies extend southward along the coasts and significantly influence the hydrology in the region. Fluctuations in surface ocean temperature, whether daily, seasonal or interannual, have a significant impact on exchanges between the ocean and the atmosphere. Understanding the variability of ocean conditions in this region and its links with climate and atmosphere is therefore of great interest for two main reasons [6]:

a) The Gulf of Guinea is the main source of water vapor generating the majority of precipitation on the continent;

b) This area of the tropical Atlantic experiences the greatest seasonal range in surface ocean temperatures, approximately 5°C to 8°C.

The results from this oceanographic campaign clearly illustrate the typical environmental characteristics of the warm season in the studied region. A deep oligotrophic surface layer with low fluorescence concentrations and a strong pycnocline defines the upper water

column. This marked density stratification acts as a barrier, limiting the vertical exchange of nutrients between deep and surface layers. Consequently, a Deep Chlorophyll Maximum (DCM) forms within the pycnocline, where the intersection of light and nutrients creates optimal conditions for phytoplankton biomass. Furthermore, ADCP and LADCP data confirmed the presence of key regional currents, including the North Equatorial Counter Current (NECC), the Guinea Current (GC), and the South Equatorial Current (SEC). Ultimately, while these findings are significant, further sea campaigns remain essential to capture the full variability of oceanic physical parameters and circulation patterns necessary to understand the complex regional dynamics influencing Liberia's oceanographic and biological processes.

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Author contributions:
Both authors conceived the idea for this publication. I. Bessa drafted the original manuscript in French, lead the oceanographic campaign and data analysis. R. Daniels contributed to the oceanographic data collection and translation of the original manuscript to English. All authors contributed equally to the writing and editing of the manuscript.

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The authors declare that there is no conflict of interest regarding the publication of this article.

Authorship
I, Roosevelt S. Daniels, corresponding author, hereby confirm that I have read the Springer Nature, Discover Oceans journal policies and is submitting this manuscript in accordance with those policies.

Data Availability
The data for this research is available upon request from NaFAA as per the terms of its data sharing protocol.

Ethics Approval

This study did not involve human participants, human data or tissue, or experiments on animals. It is based solely on physical, chemical and meteorological oceanographic measurements (CTD, ADCP, LADCP, thermosalinograph, fluorimeter and nutrient water samples) collected during a research survey in Liberia's Exclusive Economic Zone.

Consent to Participate

Not applicable. The study involved no human participants.

Consent to Publish

Not applicable. The manuscript contains no individual person's data, images or other identifying details.

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