SPATIO-TEMPORAL VARIATION OF SEA SURFACE TEMPERATURE (SST) AND MARINE CHLOROPHYLL CONCENTRATIONS ALONG THE ALGERIAN COAST (SE ALBORAN SUB-BASIN AND ALGERIAN SUB-BASIN)

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Abstract. The analysis of satellite images allowed us to define the variation of marine chlorophyll (Chl-α) combined with Sea Surface Temperature (SST) variation along the Algerian coast. The database was downloaded daily from the MODIS Aqua satellite between 2008 and 2018 and classified by month. Processing of the satellite images showed significant thermal variations between the West, Centre, and East of the coast, accompanied by local fluctuations in chlorophyll variation. The correlative study between the Spatio-temporal variations of SST and Chl-α indicates a strong negative correlation at the temporal scale (r=-0.92) and a weak negative correlation at the spatial scale (r=-0.39). These results indicated that Chl-α was influenced by seasonal changes in SST and marine hydrodynamics and local anthropogenic inputs. Furthermore, the principal component analysis (PCA) between the Spatio-temporal variations of SST and Chl-α allowed us to classify the Algerian coast into two sub-basins: the southwestern (S.E.) Alboran sub-basin and the Algerian sub-basin, as well as a central transitional zone between the two sub-basins. The study showed that satellite images could determine the Spatio-temporal relationship between SST and Chl-α variations and understand marine ecosystems' functioning.

Key words: SST; Chl-α; correlation; SE Alboran sub-basin; Algerian sub-basin.

INTRODUCTION

Physical and biological processes in marine ecosystems vary spatially and temporally and are closely interrelated. SST and Chl-α are the essential oceanographic parameters for studying physical and biological conditions [22] and are commonly used to predict potential fishing grounds [26, 34]. Indeed, these parameters can indicate the availability of food resources in an ecosystem when exploring fishery resources [24]. On the one hand, SST plays an essential role in global climate change [28], and on the other hand, the pigment concentration of Chl-α is a valuable index of phytoplankton biomass [24]. Indeed, the variability of Chl-α is related to seasonal monsoon due to changes in water conditions such as SST that influence phytoplankton growth [28]. Therefore several studies have shown a close coupling between SST and Chl-α [20, 22, 33].

Exploiting satellite images to extract marine parameters is an efficient and effective alternative to oceanographic campaigns that cover a limited geographical area and require expensive and time-consuming work. Satellite sensors allow more efficient spatial and temporal distribution analysis that can be measured from space [27] and provide reliable global ocean coverage of SST and Chl-α at high spatial and temporal resolution. This is the only way to monitor changes in the marine ecosystem on a global scale [15]. Chl-α, a proxy for phytoplankton biomass, extracted from satellite imagery, provides information on the biological production area, while SST can explain its variation [22, 24] with other factors, such as light, nutrients, stratification of the water column, etc. The use of these two parameters would improve our understanding of physical and biological processes in the oceans and seas [15], periods of high productivity [18], and the availability of food resources in an ecosystem for better exploration of fishery resources [24].

The Alboran sub-basin and the Algerian sub-basin, with their different characteristics, are critical areas for the general circulation of the western Mediterranean basin and the whole Mediterranean sea. The basin has an intense water inflow/outflow regime with complex circulation patterns involving freshwater from the Atlantic and saltier water from the Mediterranean [2]. Despite the importance of these two sub-basins, there are very few studies published by local researchers interested in understanding the functioning of their ecosystems, in particular, in determining the spatiotemporal variations of biotic and abiotic parameters along the Algerian coast. For example, Nacef *et al*. (2016) [18] studied temperature and salinity variations over 40 years throughout the Mediterranean, including the western basin. He concluded that the western basin is less warm and salty than the eastern basin, thus noting a thermal solid and saline gradient from west to east across the Mediterranean. This gradient is also observed by the same author on a small scale along the Algerian coast. In the light of these results, the theme of this paper is based on the Spatio-temporal variation of temperature and Chl-α on the Algerian coast, and leads us to ask critical questions that are the focus of this paper, such as: were there contrasting patterns of variability for SST and Chl-α in the Alboran and Algerian sub-basins? What were the main environmental characteristics that force these patterns? The objective of this paper was to answer these questions to define the Spatio-temporal variability of Chl-α and SST along the Algerian coast by studying their distribution and correlation.

MATERIAL AND METHODS

Presentation of the study area

According to the division of the Mediterranean basins, the Algerian coast was subdivided into two sub-basins: the South-East (S.E.) of Alboran sub-basin from 2°W to 0°5'E (Algerian-Moroccan borders) and the Algerian sub-basin from 0°5'E to 8°40'E (Algerian-Tunisian borders) (Fig. 1). The study was carried out on the entire Algerian coast (southwestern Mediterranean) to achieve our aim. To carry out the sampling, we chose the bays for the economic interest they represent, given that fishing harbors were built in them. Four bays were located in the Alboran sub-basin (from 1 to 4), and six bays were located in the Algerian sub-basin (from 5 to 10) (Fig. 1).

Satellite image processing

The MODIS Aqua EOS PM-1) sensor was chosen for its spectral resolution, with 9 bands used to observe the color oceans.

SST and Chl-α extraction

Satellite images were downloaded daily at 15 km from the shoreline to extract SST values and Chl-α concentrations to move away from coastal suspended solids that may distort the results. The download was done over 10 years (2008-2018) by using the internet website (https://www.nasa.gov/) Level 2 (4 km) to access to database of GSFC (Goddard Space Flight Center) of NASA (National Aeronautics and Space Administration). Images downloaded were then stored by month and year, selected in a clear sky (cloud cover for SST and Chl-α were removed to ensure an efficient reconstruction). From daily image, we later average them into monthly mean data for further data analyses. The extraction of the information was done using the software ENVI 4.8; data were displayed by clicking on the pixel, then the extreme values were removed. To extract the Chl- α concentrations per station, we selected one point in each station and 8 points around it, and calculated their mean to obtain a single value per station. This was done on the downloaded daily images. Final data were used to calculate the averages and standard deviations. The results obtained were classified in a spreadsheet that combines the SST and the Chl-α values for each month for each region. We calculated the mean values of SST and Chl-α in the 10 regions to understand their variability and have a global view of their spatial and temporal variation (Fig. 2).

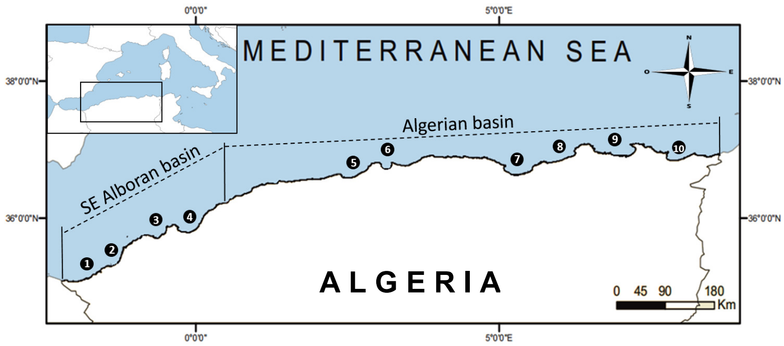

Figure 1. Map of the sampling area. The numbers correspond to bays. (1): Tlemcen; (2): Ain Temouchent; (3): Oran; (4): Mostaganem; (5): Tipaza; (6): Algiers; (7): Bejaia; (8): Jijel; (9): Skikda and (10): Annaba.

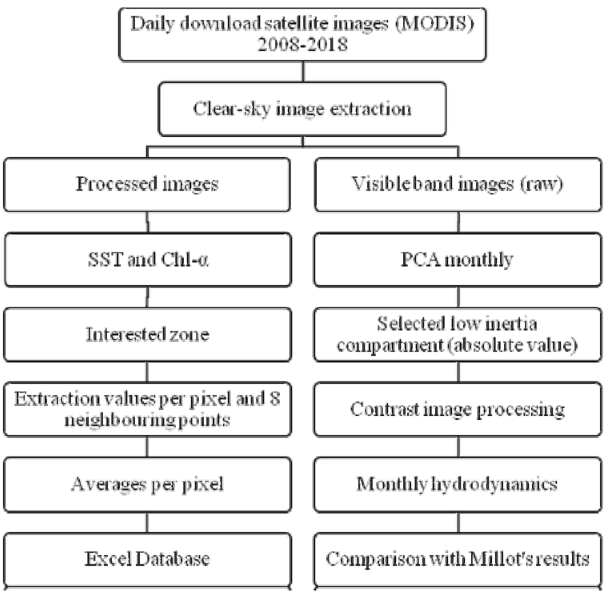

Figure 2. Flow chart of the method used

Surface current

The images used were directly accessible via the LP DAAC (Land Processes Distributed Active Archive Center) website (https://earthexplorer.usgs.gov/). We used visible images with two resolution products: MYDO9GQ 250m and MYDO9GQ 500m and ENVI 4.8 calibration software. To map the surface current on the Algerian coast, we used a new framework developed in our laboratory; we applied PCA on the downloaded images in order to classify them, and using Millot's results as a reference, we noticed that the low inertia channel presents the images that characterize the hydrodynamics of the Algerian coast (Fig. 2). We had mapped the surface current in each sub-basin separately to extract the necessary information better.

Data analysis

The correlation coefficient (r) was used to analyze the relationship between SST and Chl-α. However, to define groups with similar behavior of the studied parameters on the Algerian coast, a principal component analysis (PCA) was used. The analysis of the data was done on the XLSTAT appendix downloaded on the Excel software.

RESULTS

Satellite results

The overall rate of missing SST values and Chl-α concentration in the image bank was 7%. This lack of data was mainly due to the cloud structures present in the atmosphere over the target area and during the winter season, when the atmosphere was more frequently loaded with aerosols.

Satellite images were used to visualise the distribution of SST and Chl-α according to colour. For SST, the warmest regions were coloured red and the coldest regions were coloured blue, while regions with intermediate temperatures were coloured green and yellow (Fig. 3). The regions in red were located in the Algerian sub-basin, notably in the extreme east between 7°E and 9°E, and outside the bays at 4°E. While the blue areas were located mainly in the SE of the Alboran sub-basin, in particular in the bay of Oran (0.5°W), and in the west and centre of the Algerian sub-basin. The green and yellow areas were located mainly in the Algerian sub-basin, then in the SE Alboran sub-basin, This thermal spatial distribution was identical in all months with the thermal variations that accompany the seasons (Fig. 3). The spatial distribution of Chl-α indicated low concentrations marked by violet and blue, which were located all along the Algerian coast and mainly in the SE of the Alboran sub-basin throughout the year, while in the Algerian sub-basin we noted the appearance of green, yellow and red, which indicated an increase in Chl-α concentrations in winter and spring (between December and May) (Fig. 4).

Sea Surface Temperature (SST)

In general, SST followed a seasonal variation in both sub-basins. Between late spring and early autumn, the SST was higher, with a peak noted in summer, during which the solar intensity was high, accompanied by a shallow cloud cover. Between late autumn and early spring, the SST gradually decreased to reach a peak in winter. In this period, the days were shorter and solar energy was not very intense. Nevertheless, the Alboran sub-basin was cooler than the Algerian sub-basin, especially in summer. Indeed, the SST varied between 17.5°C - 18°C in the SE Alboran sub-basin and between 18°C - 19°C in the Algerian sub-basin. There was thus a difference of about 1°C between the two sub-basins. Besides, the highest annual SST was recorded in the Algerian sub-basin (19.17°C), and the lowest value was recorded in the Alboran sub-basin (17.61°C), which corresponded to an upwelling zone.

There was a decreasing gradient in the Alboran sub-basin and thermal fluctuations in the Algerian sub-basin. This was the result of the passage of cold and dense Modified Atlantic Water (MAW), which circulated on the surface of the coast. Therefore, the western region was directly exposed to this current, while the eastern region was closer to the physical conditions of the Mediterranean basin (warm and dense waters).

Marine chlorophyll concentration

According to the graphical representations (Fig.4), Chl-α concentration followed an inverse seasonal variation concerning SST. Indeed, between late spring and early autumn, the concentration decreased to a minimum value at the height of the summer season and continued until the autumn season despite the intense insolation. This was due to the depletion of nutrients in the environment used by phytoplankton during photosynthesis and the decrease in the rate of precipitation, thus adding the effect of grazing by other organisms. Between late autumn and early spring, the Chl-α concentration was at its highest during this period, to the increase in the precipitation rate, thus the renewal of nutrients from the demineralization of organic matter and to the input of wadis rich in nutritive salts and suspended solids (S.S.). The two sub-basins had similar chlorophyll production, with an average of 0.4 $mg \cdot m^{-3}$, with the highest value was noted in the Alboran sub-basin in March (1.03 $mg \cdot m^{-3}$). The lowest and highest annual Chl-α were recorded in the Algerian sub-basin (Ski: 0.307 $mg \cdot m^{-3}$ and Alg: 0.523 $mg \cdot m^{-3}$ respectively). Alg bay was rich in Chl-α throughout the year and was continuously fed by land-based discharges that enriched the marine environment.

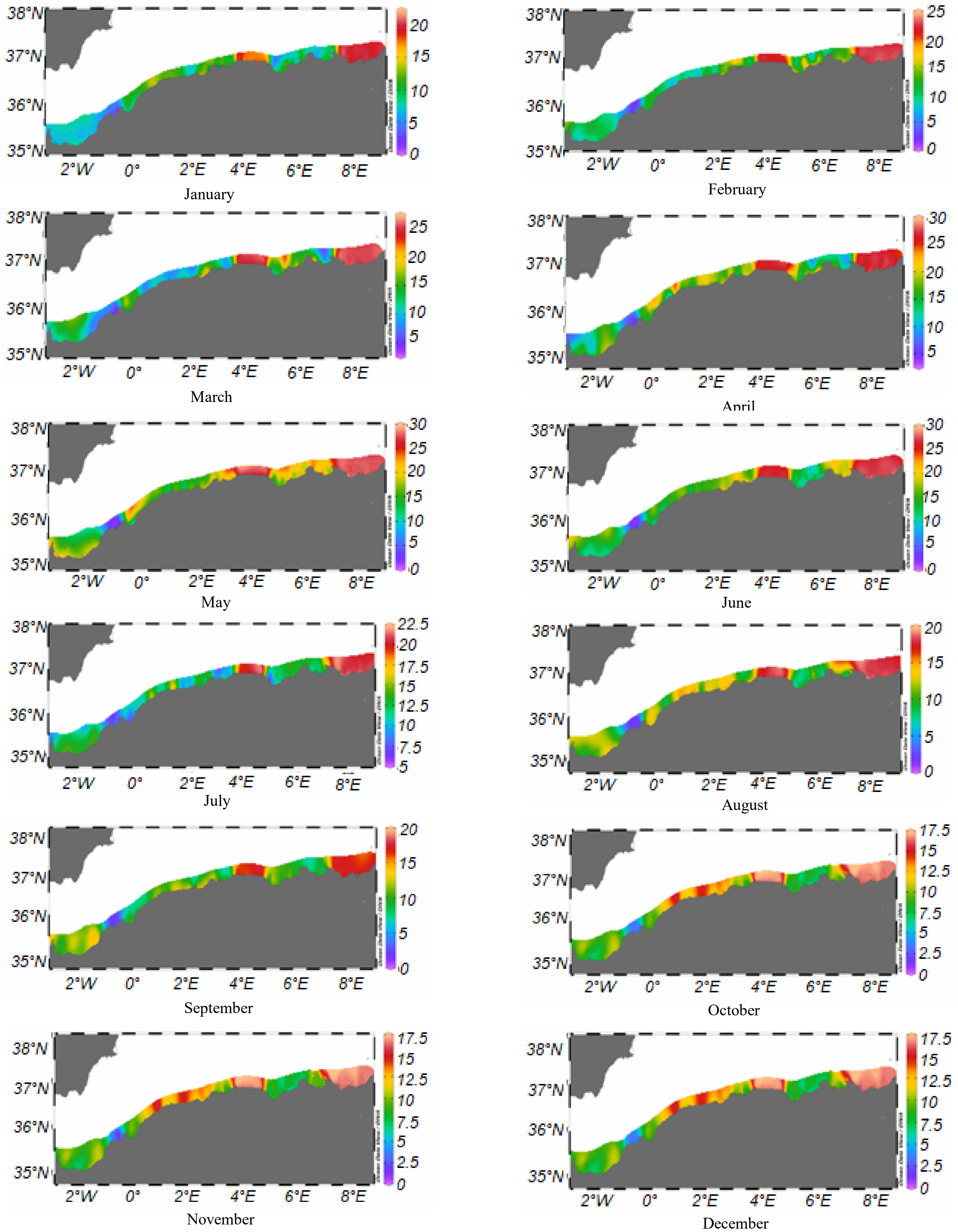

Figure 3. Distribution of monthly means (2008 to 2018) of Sea Surface Temperature (SST) along the Algerian coast

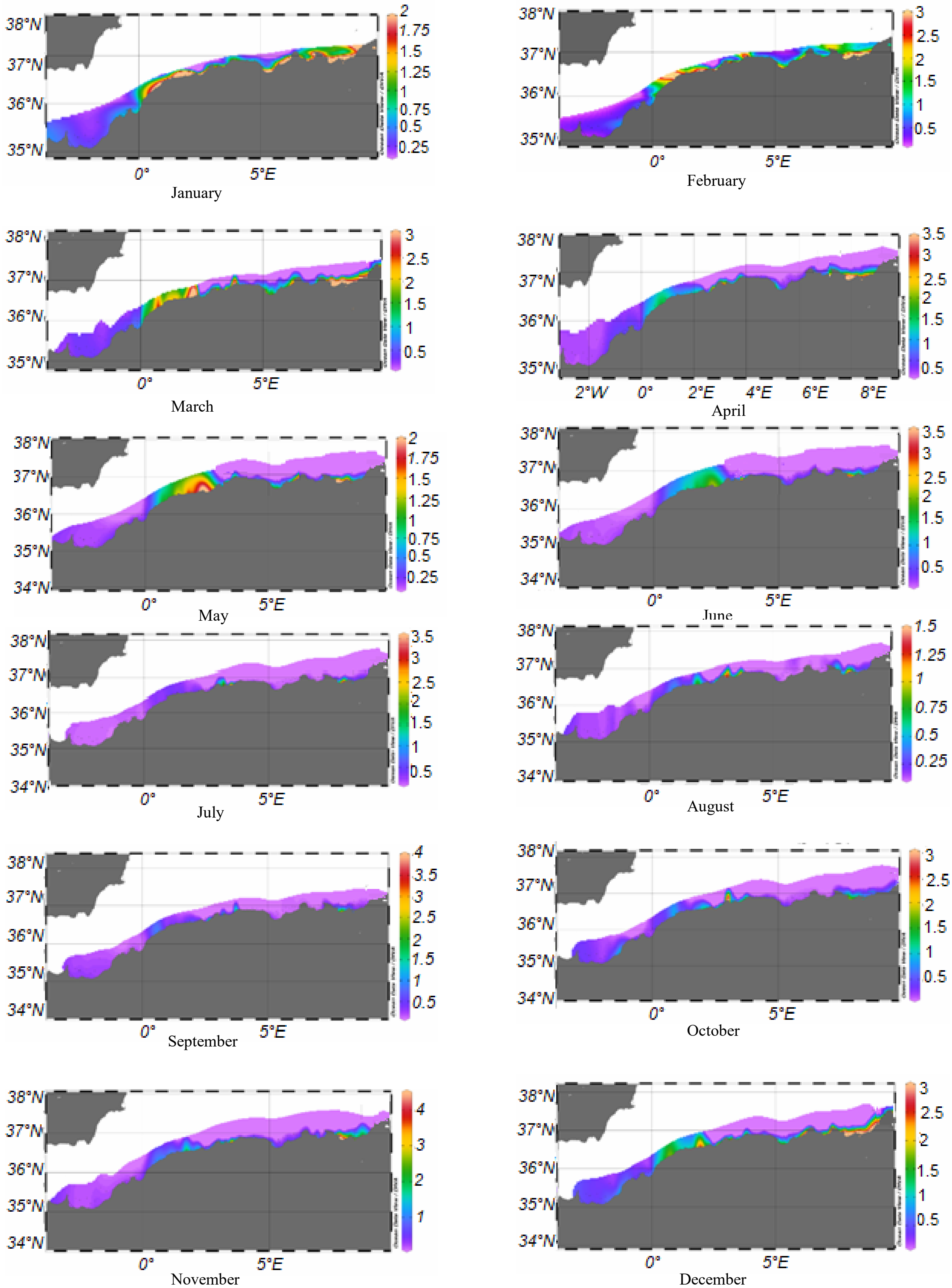

Figure 4. Distribution of monthly means (2008 to 2018) of chlorophyll (Chl-α) concentrations along the Algerian coast

Spatial and temporal variability of SST and Chl-α (by month and by the bay)

The graphical illustrations below summarised the analysis of the Spatio-temporal distribution of biotic and abiotic parameters (Chl-α and SST). The temporal variation (Fig. 5-a_1) showed all regions' average monthly SST and Chl-α measurements. The monthly variations of SST and Chl-α evolved inversely, we could see that Chl-α concentrations decreased with increasing SST between May and October with maximum SST value in August and conversely, Chl-α increased with decreasing SST between December and March where maximum value of Chl-α were recorded (Fig. 5-a_1). The spatial variation (Fig. 5-b_1) showed the

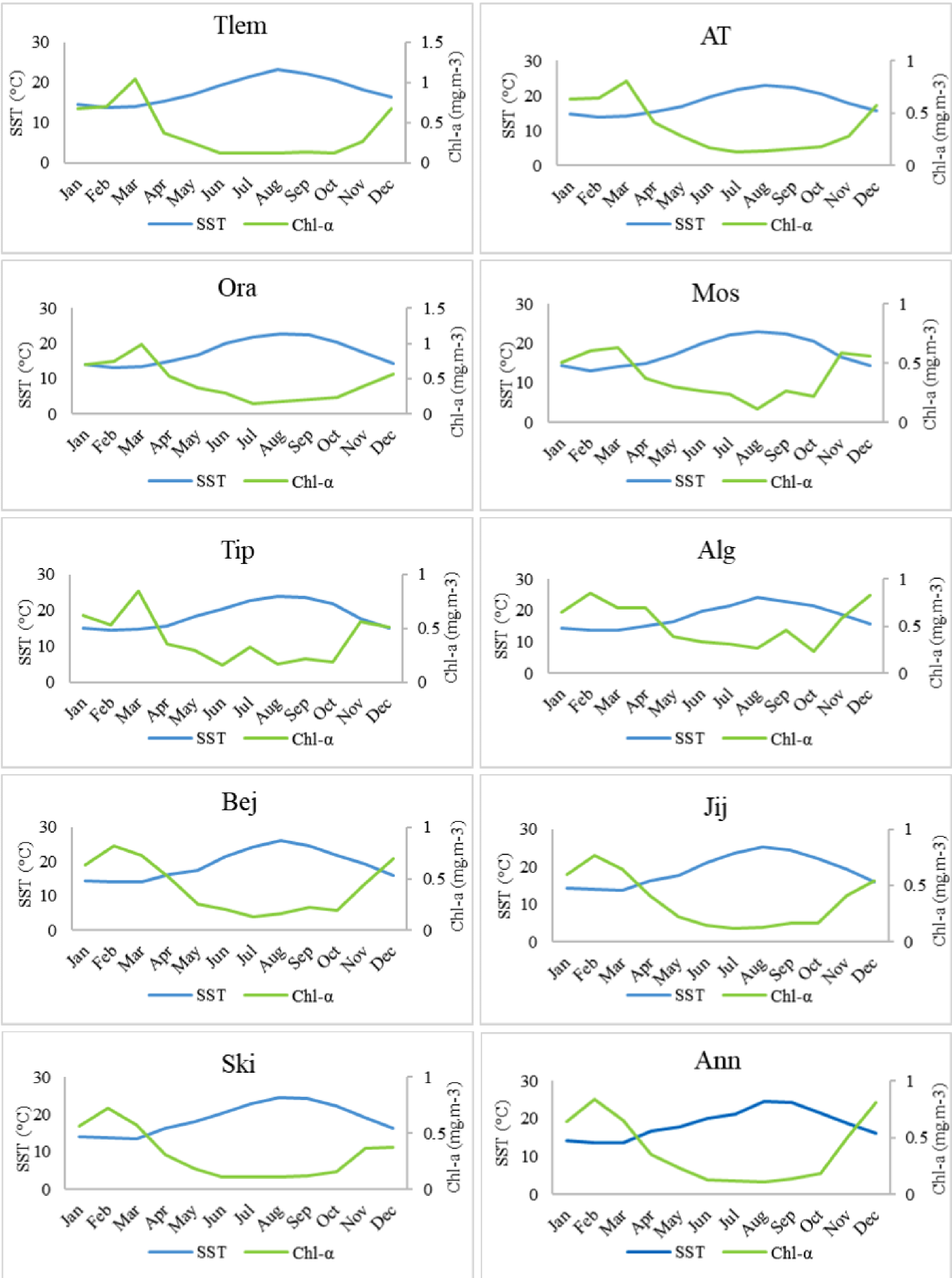

Figure 5. Graphical illustration of temporal variations SST and Chl-α in each by.

annual averages of the regional SST and Chl-α measurements for each region. Overall, the SST and Chl-α parameters in the study regions showed significant fluctuations and varied simultaneously. From this graph, the AT, Tip, and Ann regions did not show a clear negative relationship between SST and Chl-α. Meanwhile, the Tlem, Ora, Mos, Alg, Bej, Jij, and Ski regions showed inversely correlation between SST and Chl-α (Chl-α concentrations increased with decreasing SST). We noted the intersection of the curves between TSM and Chl-α at Tip (Fig.5-b_1).

Correlative study SST/ Chl-α

The correlative study between SST and Chl-α was carried out using the data used in the previous illustration, namely the temporal variation of monthly average SST and Chl-α measurements of all regions (Fig. 6-a_2), and the spatial variation of average regional SST and Chl-α measurements for each month (Fig. 6-b_2). The linear correlation between the temporal variation by month of SST and Chl-α (Fig. 6-a_2) showed a strong negative correlation between these parameters (r= -0.92). At the same time, the spatial correlation by the bay (Fig.6-b_2) was also negative but lower (r=-0.39) (Fig. 7).

Principal Component Analysis between SST and Chl-α

PCA allowed us to see the position of areas that represent similar or opposite characteristics and confirm the Algerian coast's subdivision into sub-basins: Alboran sub-basin and Algerian sub-basin. Two groups with different characteristics and two isolated cases were identified. Each group had similar characteristics presented in the PCA (Fig. 6). The first group consists of Tlem, AT, Ora and Mos. All these regions were located on the west coast (Alboran sub-basin). Low temperatures and high Chl-α concentrations characterized this group. The second group consists of Bej, Jij, Ski, and Ann. All these regions were located on the east coast (Algerian sub-basin). High temperatures and low Chl-α concentrations characterized this group.

The two isolated cases concern first the Tip region where we recorded average SSTs and average chlorophyll concentrations; this region was the closest to the center of the PCA representation to consider this region as a reference area. Low SSTs characterized the Alg region compared to the Algerian sub-basin regions and high chlorophyll concentrations. We could see the subdivision of the Algerian coast according to the distribution of Chl-α and SST, which confirms the division of the coast into two sub-basins: the Alboran sub-basin, which was composed of the regions Tlem, AT, Ora and Mosta, the Eastern Algerian sub-basin which was composed of Bej, Jij, Ski, and Annaba, as well as the Central Algerian sub-basin which was composed of Alg and Tip which constituted a transitional area between the two sub-basins.

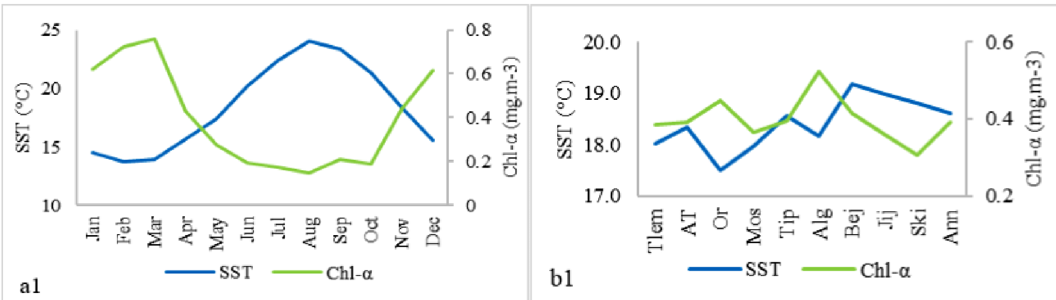

Figure 6. Temporal (a_1) and spatial (b_1) variation of SST and Chl-α

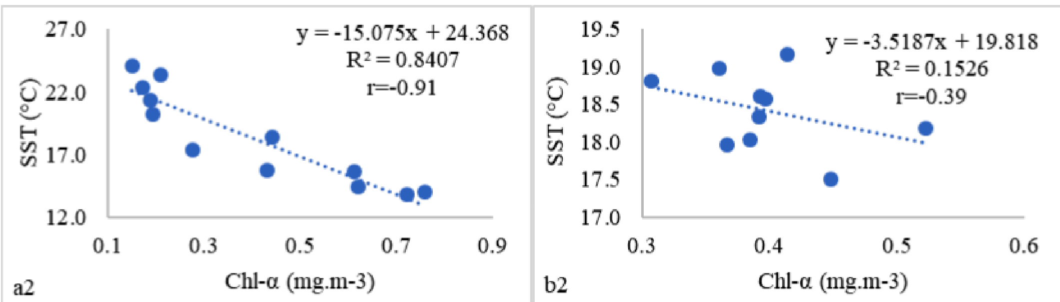

Figure 7. Correlation scatter plot of the temporal (a_2) and the spatial (b_2) variation of SST and Chl-α

The surface current along the Algerian coast

To better understand and explain the distribution of SST and Chl-α parameters in the SE Alboran sub-basin and the Algerian sub-basin, it was more informative to see the marine surface circulation along the Algerian coast, i.e., in both sub-basins (Fig. 8). The marine traffic on the Algerian coast followed the subdivision of the Mediterranean sub-basin. The traffic in the SE Alboran sub-basin (Fig. 8-A) differed from the traffic in the Algerian sub-basin (Fig. 8-B). The Atlantic waters of the Alboran Sea generated a quasi-permanent anticyclonic gyre in the west (Moroccan Mediterranean coast), between 5°W and 4°W, and a variable circuit in the east (Algerian west coast: SE Alboran sub-basin), between 3°W and 1°W, which in turn created the Almeria-Oran front (AOF) (Fig. 5-A). Furthermore, cyclonic and anticyclonic eddies developed from 0° along the central and eastern Algerian coast throughout the year and then moved away towards the open sea to the north (Fig. 5-B). The circulation in the Algerian sub-basin appeared to be very turbulent, favoring the dispersion of pollution sources and the whole food chain. The information from the surface current map will be complemented and explained by previous work in the discussion section.

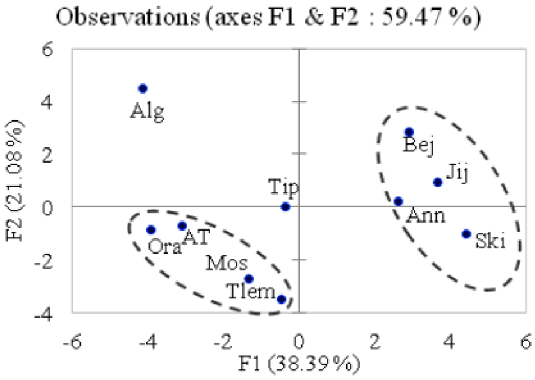

Figure 8. Principal Component Analysis (PCA) between Spatio-temporal variations in Sea Surface Temperatures (SST) and Chl-α

DISCUSSION

Spatial and temporal variations of SST and Chl-α depend on several factors, mainly solar radiation, wind direction and speed, nutrient availability, hydrodynamic circulation and associated phenomena (eddies and upwelling).

The spatial variability of SST and Chl-α is independent of solar radiation since the latter is considered constant due to the fact that the Algerian coast is lagitudinal (almost constant latitude between 35° and 36°), so this factor is almost the same for all points of the Algerian coast. However, the amount of solar energy varies according to the seasons, which are determined by weather conditions and astronomical laws [32]. It is obvious that it is more important in spring and summer than in autumn and winter, and that these seasonal variations influence thermal variations and Chl-α production.

Furthermore, the spatial variability of SST for the Algerian coast is a function of the hydrodynamic variability governed by the Atlantic water circulation and the associated hydrodynamic phenomena, and the spatial variation of Chl-α is a function of thermal variability and nutrient availability.

Temperature measured by satellite showed a gradual increase from west to east. Indeed, the SE Alboran sub-basin (from 2°W to 0°E) taked on the characteristics of Atlantic waters that was cold as they passed through the Strait of Gibraltar (between 17 and 18 °C). The surface waters of the Algerian sub-basin (from 0°E to 8°E) was becoming warmer and closer to the characteristics of Mediterranean waters (between 18 and 20 °C). Nevertheless, despite the presence of an increasing west-east gradient, we noted some thermal fluctuations in Oran and Algiers, which we have explained by very detailed previous research that we have exploited in our study to better understand the SST/Chl-α relationship along the Algerian coast.

Apart from the thermal fluctuations at Oran, the SST at Tlemcen (2°12'24W and 1°35'11W) was the lowest in the SE Alboran Basin due to the surface circulation of cold Atlantic waters in the form of cold pockets east of 3°W [8]. Indeed, Baldacci *et al.* (2001) [4] and Tintore *et al.* (1998) [30] confirmed the permanent presence of the gyre to the east of the Alboran Basin between 3°W and 1°W (resulting in the permanent formation of the Almeria-Oran front), but its structure was unstable in terms of its seasonal displacement and thickness; the gyre moved regularly throughout the year towards the east and west of the Alboran sub-basin, with an intense presence in the

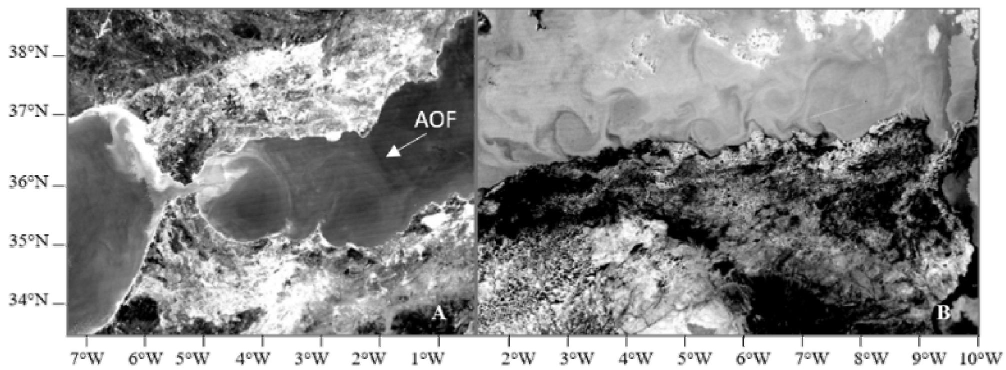

Figure 9. MODIS satellite image of surface current on the Algerian coast. A: Alboran sub-basin. B: Algerian sub-basin. AOF: Almeria-Oran Front.

summer [12]. Moreover, Parada and Canton (1998) [21] have shown that the gyre center has relatively higher temperatures than outside, and therefore a slight temperature drop was recorded in Oran and Mostaganem bay, where the water from the east anticyclonic gyre flows (Almeria-Oran front). In addition, Oran bay was characterised by seasonal upwelling of nutrient-rich water, which maked it the richest in Chl-α in the SE Alboran sub-basin [20]. Indeed, Bakun and Agostini (2001) [3] have shown that the predominant westerly winds in the Alboran Sea tend to induce surface Ekman transport towards the coast and corresponding upwelling on the Spanish side and seaward transport and downwelling on the African side of this area of the Mediterranean, i.e. the Oran region. However, in late summer and autumn, the trend was reversed producing an offshore Ekman transport by the winds inducing an upwelling of the Algerian coast, and a coastal transport and downwelling off southern Spain.

The Bay of Algiers, located in the centre of the Algerian sub-basin, maintained a cold SST due to a cold eddy close to the coast, which acts as a paddle wheel driving cold Atlantic waters clockwise around its perimeter, first offshore near the Balearic Islands and then towards the African coast [29]. The medium temperature at the bay of Jijel and Skikda (between 5°39'33E and 7°12'49E) can be explained by the presence of a late spring eddy near the Algerian coast at 6°E. This eddy conducted the waters of the northern basin, which was colder and gradually mixing with the Mediterranean waters, towards the Algerian coast [17]. Between the two eddies formed at Algiers bay and the bays of Jijel and Skikda lied Bejaia bay, which does not seem to be affected by the cold Atlantic waters derived from the eddies. Thus, Bejaia bay appeared to be warmer than the rest of the coast.

Concerning the distribution of the chlorophyll concentration, Boudjnah *et al.* (2019) [7] noted that there was a decreasing west-east gradient of Chl-α concentration where the Alboran sea was richer in Chl-α (precisely at the bay of Tlemcen) than the Algerian sub-basin (the lowest value in the bay of Skikda). Nevertheless, in our study, the gradient was not observed, but the lowest value recorded in Skikda bay was confirmed (0.307 $mg.m^{-3}$), and the high value was noted in Alg bay (0.52 $mg{\cdot}m^{-3}$).

A similar chlorophyll production was observed in both sub-basins in our study, with the fluctuations related to SST variations explained above by hydrodynamic activity and associated hydrological phenomena. Boudjnah *et al.* (2019) [7] also found similar concentrations in the two sub-basins in spring, with average values varying between 0.26 and 0.29 $mg{\cdot}m^{-3}$. He further explained this similarity by a homogeneous distribution of nutiments in the two sub-basins, namely dissolved nitrate (NO_3^{2-}), nitrite (NO_2^{2-}), Silicium (SiO_2), except for reactive phosphate (PO_4^{3-}) where concentrations are higher in the Algerian sub-basin than the SE Alboran sub-basin. This could be explained by the increased input of nutrients of terrestrial origin, considerably enriched in PO4, into the Algerian sub-basin [13].

Nevertheless, it seems that the Alboran sub-basin should be more productive than the Algerian sub-basin since Atlantic waters, upwelling, and the Almeria-Oran front enriched it, whereas the Algerian sub-basin was fed exclusively by land-based discharges. Indeed, 70% of the rivers in northern Algeria flowed into the Algerian sub-basin without treatment [31], and rainfall was more abundant in the Algerian sub-basin than in the SE Alboran sub-basin [16], favoring the flow of water towards the sea and the eutrophication of the area.

We noted two cold and Chl-α rich regions with two causes: Ora in the Alboran sub-basin and Alg in the Algerian sub-basin. The first corresponded to the upwelling phenomenon of cold water rich in Chl-α in the Oran region [6]. The second was caused by the rivers that flowed into the Bay of Algiers, bringing up cold water rich in nutrients, since the Bay of Algiers was fed by two large wadis (El Harrach and El Hamiz) that drained large quantities of anthropogenic waste [1, 4].

Furthermore, Grimes *et al.* (2010) [11] concluded that the bay of Oran and Tipaza, in particular, appeared to have a better ecological status than the other sites due to the absence of rivers flowing into these bays. Indeed, we noted that the Tipaza region was characterized by low SSTs and chlorophyll concentrations, making it a reference area. We noted thus in on more minor scales, there were significant regional anomalies [10] such as upwelling and anthropogenic discharges, and we can conclude that fluctuation of chlorophyll concentrations along the Algerian coasts was the result of the superposition of the biological pump and the estuarine reverse circulation (wadis and anthropogenic activity) [9].

We concluded that the spatial and temporal variations of SST along the Algerian coast were governed by the particular currentology of the Alboran and Algerian sub-basins. The variations of SST strongly influenced the temporal variations of Chl-α. In contrast, its spatial variations were linked to both SST and natural and anthropogenic discharges. Our results agree with previously published research [15] and find that SST has essential impacts on the Spatio-temporal distribution of marine Chl-α concentrations.

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