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Research Article

Assessment of the Marine Thermal Signal in the El Jadida Coastal Region (Atlantic Morocco) and Potential Implications for Gelidium Populations

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The El Jadida coastal region on the Moroccan Atlantic coast is affected by seasonal upwelling and has long-standing socio-economic relevance because of the exploitation of red seaweeds of the genus Gelidium, used for agar production. This study evaluates the marine thermal signal in this region and discusses its potential ecological implications for Gelidium populations. Monthly sea surface temperature (SST) series were extracted from NOAA OISST v2.1 for three points: B, an offshore reference point; D, a near-offshore point; and C, a targeted coastal point close to the Gelidium-relevant shore. The analysis covers 528 months from January 1982 to December 2025. Monthly climatologies, annual means, linear trends, seasonal anomalies, differences between early and recent periods, and spatial contrasts were computed. A Copernicus Marine Atlantic L4 reprocessed SST product at 0.05° resolution was also used to provide a complementary fine-scale spatial interpretation for February and August 2025. Annual warming was detected at the three points, with trends of +0.095 °C per decade at B, +0.060 °C per decade at C, and +0.130 °C per decade at D. The strongest seasonal warming occurred in spring, whereas summer showed the weakest trends, particularly at the coastal point C, where the summer trend was slightly negative (-0.018 °C per decade). Copernicus data confirmed that C was cooler than the offshore and near-offshore points, particularly in August 2025. These results suggest that the El Jadida coast is not characterized by a spatially uniform warming signal. Instead, the thermal regime is modulated by coastal processes, including summer upwelling. Because the present work focuses on SST alone, it should be interpreted as an environmental baseline rather than as a direct biological diagnosis of Gelidium beds. Its ecological relevance is supported by previous biological and ecological studies showing that temperature, often interacting with irradiance, nutrients, water movement, substrate conditions and harvesting pressure, can influence Gelidium population maintenance and recovery

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processes. The study therefore provides an initial climate-oriented diagnostic and a scientific basis for future field-based work on Gelidium habitats along the El Jadida coast.

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1. Introduction

The Atlantic coast of El Jadida, Morocco, belongs to a coastal domain influenced by seasonal upwelling. During the warm season, this process can bring colder and nutrient-rich waters toward the surface and the nearshore zone. This physical mechanism is well known locally: the waters of the Sidi Bouzid-El Jadida coastal sector may remain relatively cold during summer, sometimes reaching temperatures near 14 °C at the beach scale. Such a thermal regime gives the region a specific ecological and socio-economic importance.

The region is also historically associated with the exploitation of red macroalgae of the genus Gelidium, a key raw material for agar production. Morocco, Portugal and Spain have historically belonged to the main Atlantic areas where harvested Gelidium has supplied local agar producers[1]. Gelidium is especially relevant because commercial harvests are largely based on natural stocks and because the world agar market has experienced concerns related to the availability and sustainability of technical agar resources[2]. The sustainability of Gelidium habitats therefore depends not only on harvesting management but also on the evolution of physical conditions, particularly the thermal environment.

In this context, long-term SST analysis can provide a first diagnostic of the marine climate signal affecting the El Jadida coast. However, the interpretation must be cautious because regional satellite products may smooth nearshore gradients, and because the response of Gelidium populations cannot be attributed to temperature alone. Biological and ecological studies show that Gelidium populations also respond to wave exposure, substrate, water clarity, nutrients, irradiance, sedimentation, local upwelling intensity and harvesting pressure[3][4][5].

The aim of this paper is therefore to assess whether a long-term warming signal is detectable in the El Jadida marine region between 1982 and 2025, to examine its seasonal and spatial structure, and to discuss its possible implications for Gelidium habitats in light of comparisons with other Atlantic regions.

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2. Objectives

The study addresses three main questions. First, does the El Jadida region show a thermal signal compatible with background marine warming over the 1982-2025 period? Second, is this signal uniform across seasons, or is it moderated during summer by upwelling-related coastal processes? Third, do the coastal, near-offshore, and offshore points show meaningful spatial contrasts that may help interpret the potential vulnerability of Gelidium habitats?

3. Study Area and Data Sources

3.1. Study points

Three points were selected in the El Jadida coastal region. Point B was used as an offshore reference point, point D as a near-offshore point, and point C as a targeted coastal point located closer to the coast and therefore more relevant for interpreting the thermal conditions potentially affecting Gelidium habitats.

Point	Latitude (°N)	Longitude (°W)
B	33.125	-8.875
C	33.2360	-8.5741
D	33.2714	-8.6448

Table 1. *Geographic coordinates of points B, C and D.*

Figure 1. *Location of the study area and of points B, C and D offshore El Jadida. Source: Google.*

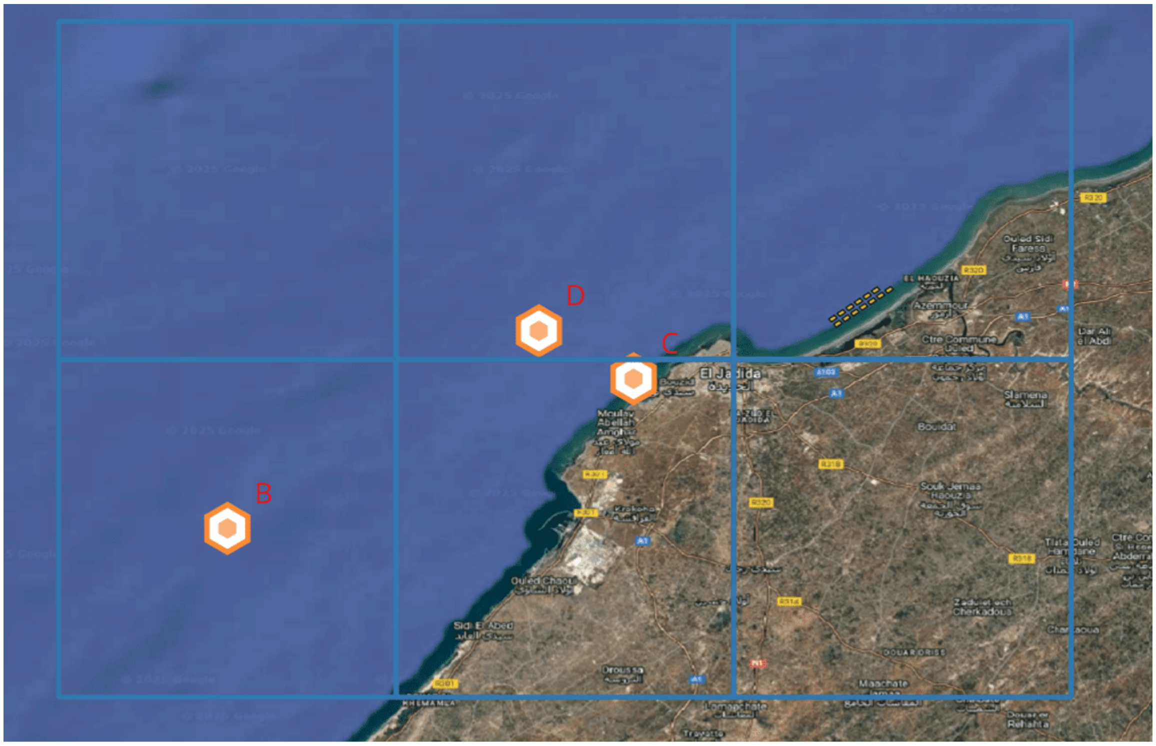

Figure 2. *NOAA OISST 0.25° grid cells in the El Jadida region and position of points B, C and D. Source: Google.*

3.2. NOAA OISST v2.1

The main calculations were based on NOAA OISST v2.1[6][7]. This product provides global SST fields on a regular 0.25° grid and is suitable for long-term climate-scale assessment. The useful monthly series extracted for this study cover 528 months, from January 1982 to December 2025, for each of the three points. Because the spatial resolution is relatively coarse compared with the nearshore geometry of El Jadida, NOAA results should be interpreted as regional-scale indicators rather than fine-scale coastal measurements.

3.3. Copernicus Marine SST product

To complement the regional interpretation from NOAA, a higher-resolution Copernicus Marine product was used: SST_ATL_SST_L4_REP_OBSERVATIONS_010_026[8]. This Atlantic reprocessed L4 SST product provides daily gap-free SST fields on a 0.05° grid. In this study, it was used for targeted spatial interpretation around points B, C and D for February 2025 and August 2025. The nearest Copernicus pixels were B: 33.125, -8.875; C: 33.225, -8.575; and D: 33.275, -8.625.

4. Methods

Let SST(y,m,p) be the monthly sea surface temperature for year y, month m, and point p. The monthly climatology was calculated as $\mathrm{Clim}(m,p) = (1/N)\ \Sigma\ \mathrm{SST}(y,m,p)$, where $N = 44$ years for the 1982–2025 period. The annual mean was calculated as $\mathrm{Ann}(y,p) = (1/12)\ \Sigma\ \mathrm{SST}(y,m,p)$. A linear trend was then fitted to annual means and expressed in °C per decade.

Monthly anomalies were calculated as $A(y,m,p) = \mathrm{SST}(y,m,p) - \mathrm{Clim}(m,p)$. Seasonal anomalies were then calculated for DJF, MAM, JJA and SON as the mean of the three monthly anomalies within each season. DJF was handled as a cross-year season. Period differences were computed as $\Delta T(s,p)$ = mean anomaly in the recent period minus mean anomaly in the early period. The periods used were 1982–2000 and 2001–2025 for MAM, JJA and SON, and 1983–2000 and 2001–2025 for DJF.

5. Results

5.1. Monthly climatology

Month	B	C	D
January	17.343	17.188	17.348
February	16.770	16.664	16.780
March	16.851	16.792	16.882
April	17.616	17.587	17.668
May	19.009	19.018	19.096
June	20.834	20.872	20.993
July	21.831	21.861	22.119
August	22.327	22.316	22.719
September	22.174	22.048	22.499
October	21.248	21.058	21.472
November	19.625	19.404	19.766
December	18.218	18.015	18.284

Table 2. *Monthly SST climatology at points B, C and D over 1982-2025.*

February was the coldest month at the three points, whereas August was the warmest month. The annual thermal amplitude, calculated as Tmax - Tmin, was 5.557 °C at B, 5.652 °C at C and 5.939 °C at D. Point D therefore showed the largest annual amplitude.

Point	Tmax (°C)	Tmin (°C)	Amplitude (°C)
B	22.327	16.770	5.557
C	22.316	16.664	5.652
D	22.719	16.780	5.939

Table 3. *Annual thermal amplitudes at points B, C and D.*

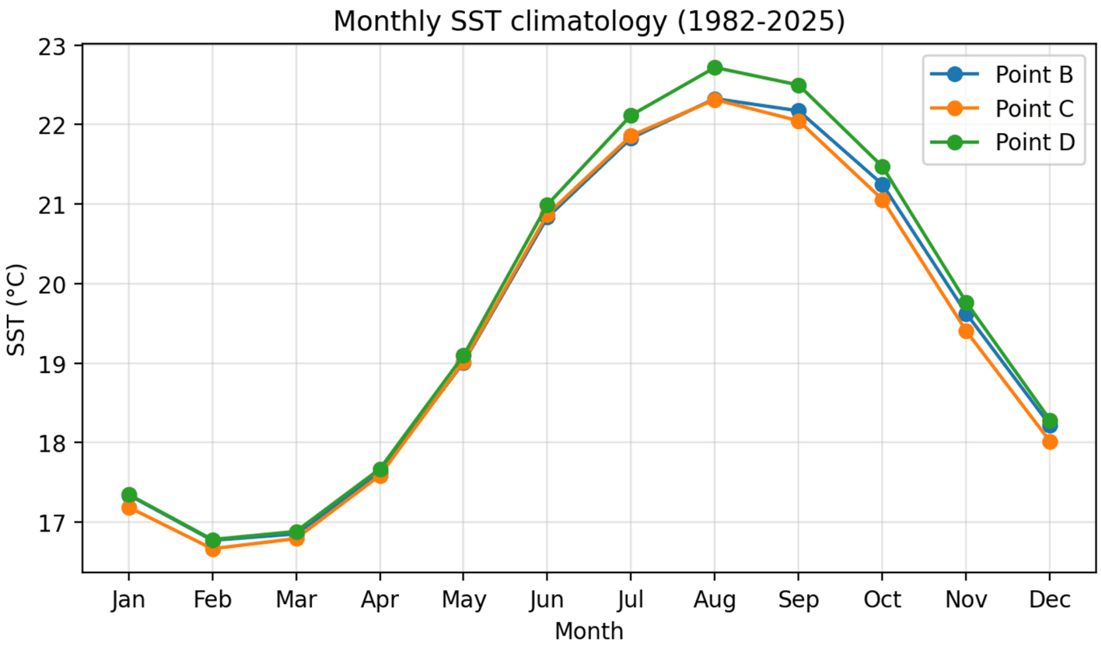

Figure 3. *Monthly SST climatology at points B, C and D over 1982-2025.*

5.2. Annual evolution and trends

The annual mean SST showed a warming signal at the three points. The strongest trend was observed at D (+0.130 °C per decade), followed by B (+0.095 °C per decade), whereas the coastal point C showed the weakest trend (+0.060 °C per decade). The comparison between the first decade (1982-1991) and the last decade (2016-2025) confirms this hierarchy, with an increase of +0.393 °C at D, +0.286 °C at B and +0.160 °C at C.

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Point	Trend (°C per decade)
B	+0.095
C	+0.060
D	+0.130

Table 4. *Annual SST trends at points B, C and D.*

Point	1982–1991	2016–2025	Difference (°C)
B	19.338	19.623	+0.286
C	19.290	19.450	+0.160
D	19.444	19.837	+0.393

Table 5. *Comparison of annual mean SST between the beginning and the end of the series.*

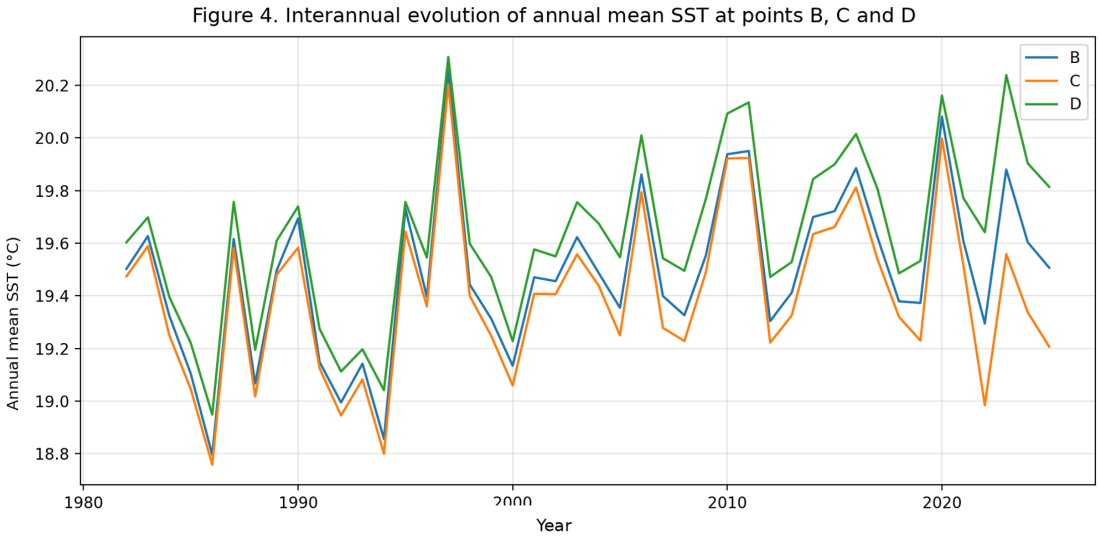

Figure 4. *Interannual evolution of annual mean SST at points B, C and D over 1982–2025.*

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5.3. Seasonal trends

Season	B	C	D
DJF	+0.148	+0.111	+0.155
MAM	+0.163	+0.147	+0.176
JJA	+0.012	−0.018	+0.097
SON	+0.076	+0.022	+0.111

Table 6. *Seasonal SST trends at points B, C and D.*

Spring (MAM) was the season with the strongest warming at the three points. Summer (JJA) was the most stable season, especially at B and C. At point C, the JJA trend was slightly negative (-0.018 °C per decade), which is consistent with the hypothesis that summer upwelling moderates coastal warming near the Gelidium-relevant shoreline.

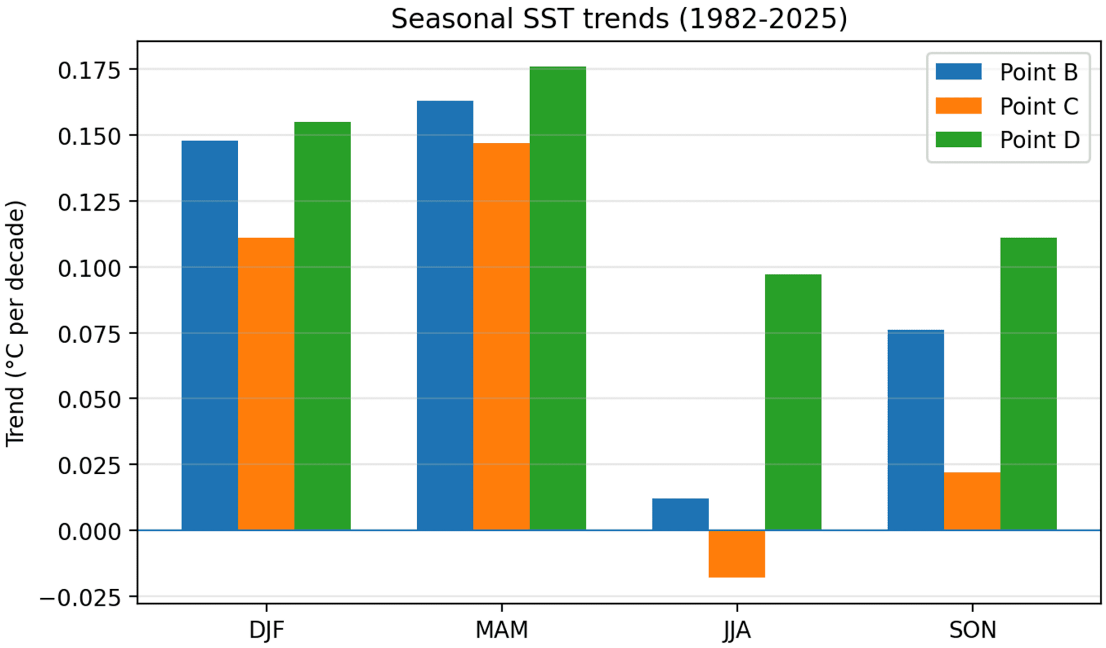

Figure 5. *Seasonal SST trends at points B, C and D.*

5.4. Mean differences between early and recent periods

Season	B	C	D
DJF	+0.259	+0.185	+0.264
MAM	+0.291	+0.269	+0.320
JJA	+0.065	+0.035	+0.252
SON	+0.369	+0.266	+0.426

Table 7. *Mean thermal differences between early and recent periods.*

The recent period was warmer than the early period in all seasons and at all points. The largest differences were found in SON and MAM. Point D again showed the strongest change, including in JJA, whereas point C remained comparatively more stable during the warm season.

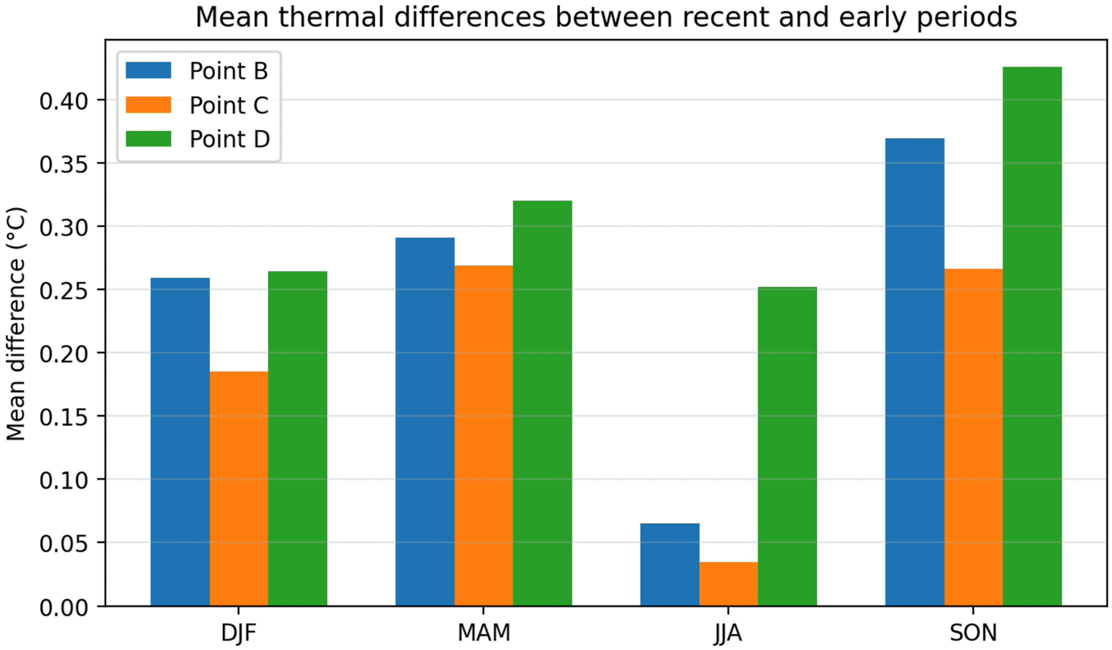

Figure 6. *Mean thermal differences between early and recent periods at points B, C and D.*

5.5. Spatial comparison between B, C and D

Season	**B**	**C**	**D**
DJF	17.444	17.289	17.471
MAM	17.826	17.799	17.882
JJA	21.664	21.683	21.944
SON	21.016	20.836	21.245

Table 8. *Absolute seasonal mean SST at points B, C and D.*

The spatial structure was not uniform. In winter, C was cooler than B and D. In summer, D became warmer than both B and C. In autumn, C remained the coolest point and D the warmest. Point B therefore behaved as an intermediate offshore reference point.

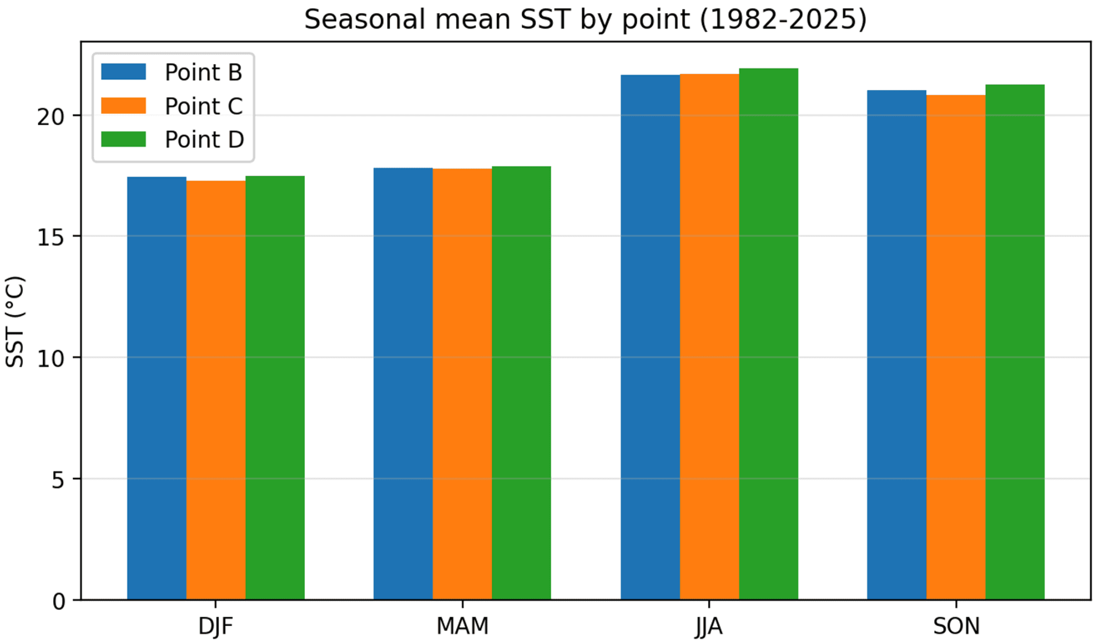

Figure 7.*Spatial comparison of seasonal mean SST at points B, C and D.*

5.6. Complementary contribution of Copernicus Marine SST

Period	**B**	**C**	**D**
February 2025	17.344	16.888	17.193
August 2025	21.855	20.531	21.033

Table 9. *Copernicus monthly mean SST extracted at points B, C and D in February and August 2025.*

The Copernicus extraction confirmed that the coastal point C was cooler than B and D in February 2025 and markedly cooler in August 2025. This supports the existence of a local coastal thermal gradient, consistent with a distinct nearshore signal at C.

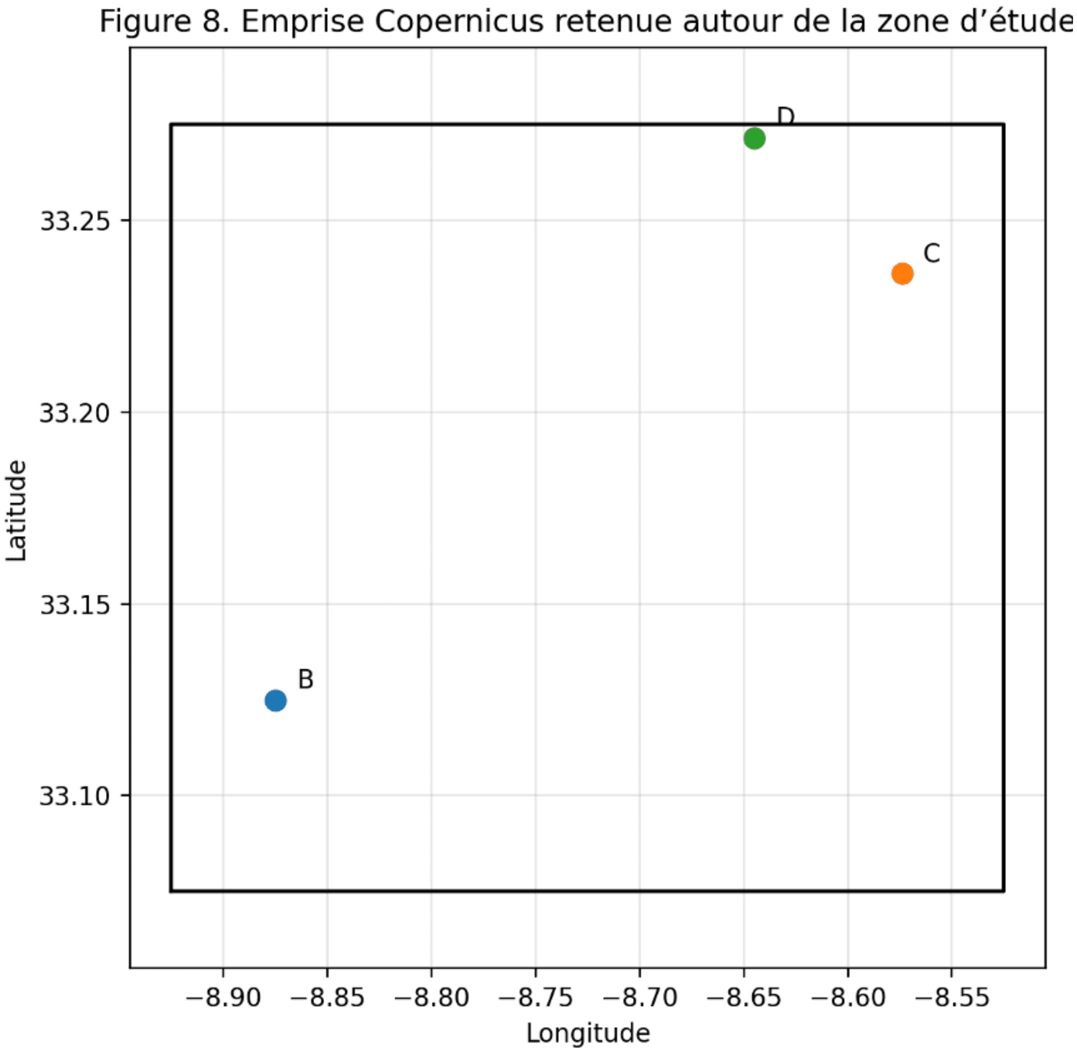

Figure 8. Copernicus SST product extent retained around the study area.

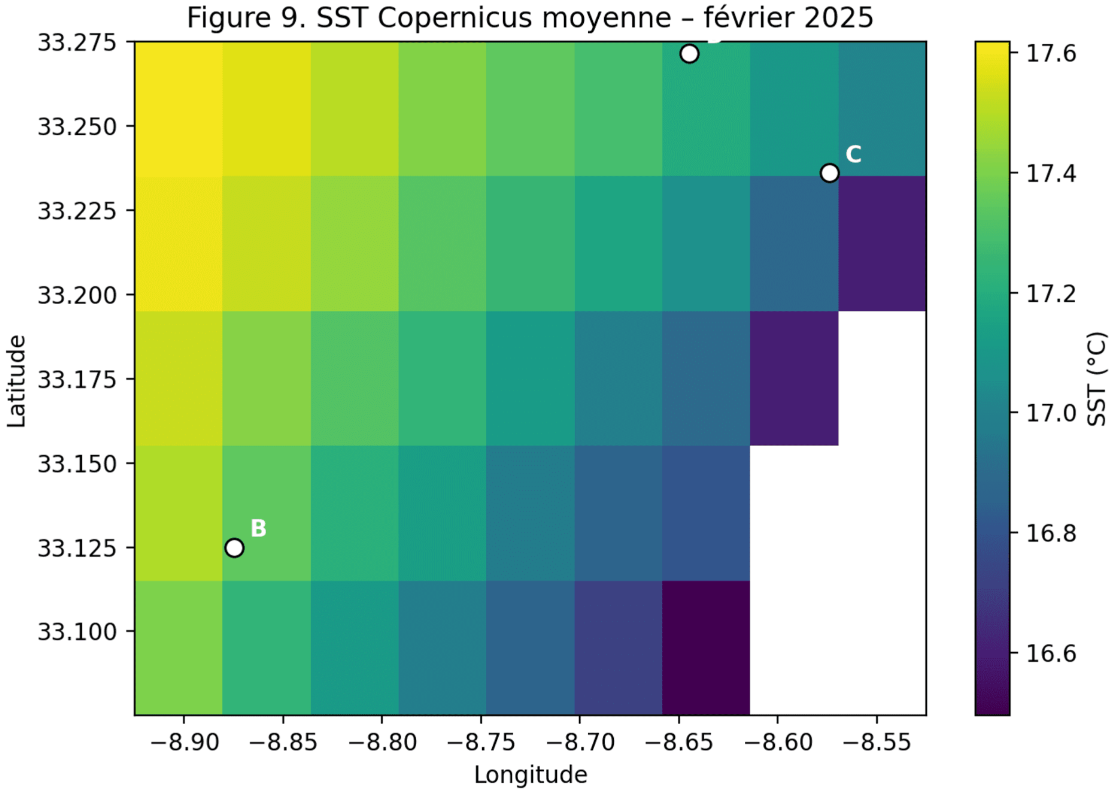

Figure 9. Copernicus sea surface temperature in the study area in February 2025, with points B, C and D.

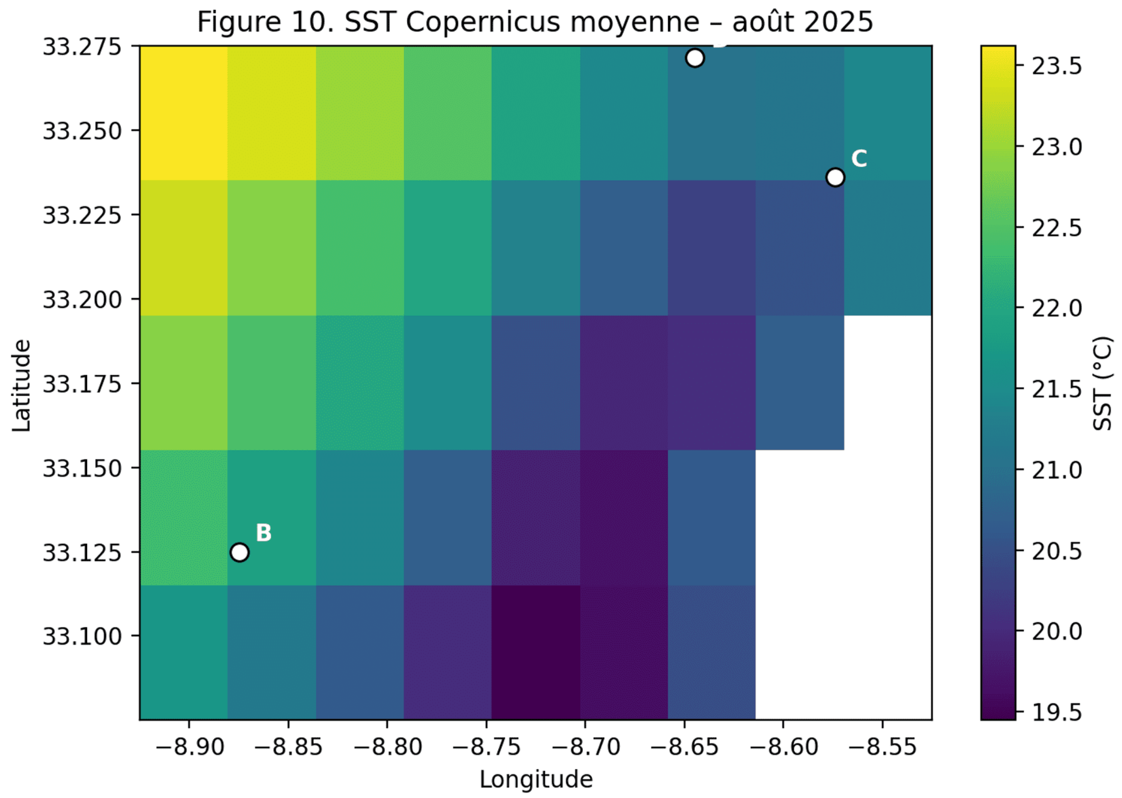

Figure 10. Copernicus sea surface temperature in the study area in August 2025, with points B, C and D.

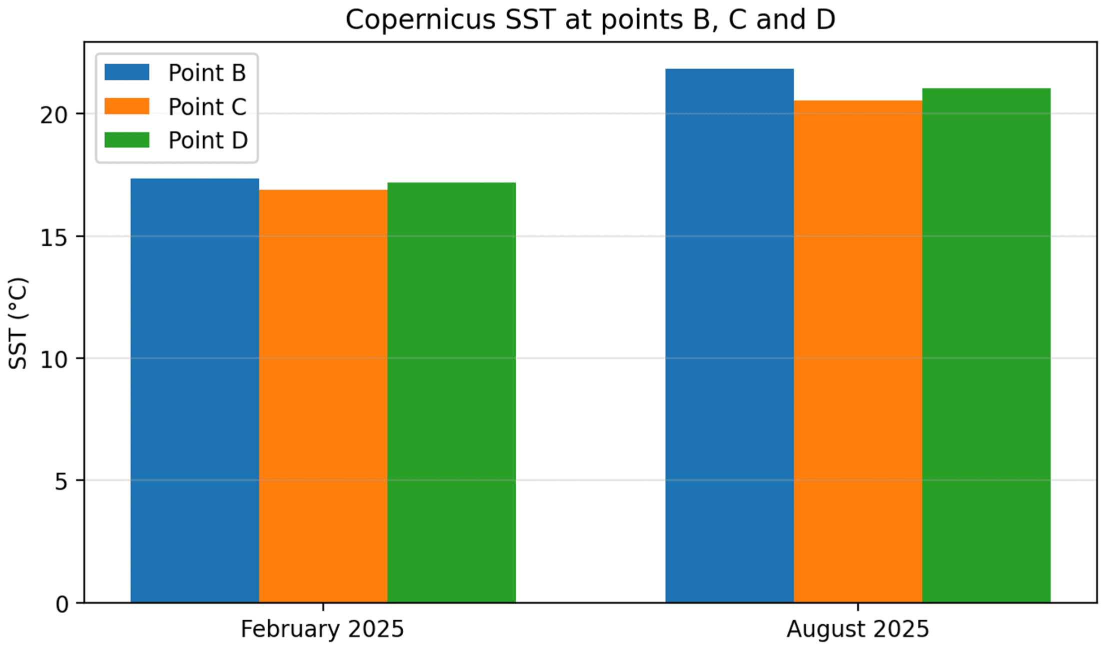

Figure 11. Comparison of Copernicus monthly mean SST at points B, C and D in February and August 2025.

6. Discussion

6.1. A warming signal with a non-uniform spatial structure

The NOAA time series indicate a positive annual SST trend at all three points over 1982-2025, confirming a background warming signal in the El Jadida marine region. However, the intensity of the signal differs spatially. The near-offshore point D shows the strongest trend and the largest increase between the early and recent decades, whereas the coastal point C shows the weakest annual warming. This result is important because the coastal zone relevant to Gelidium should not be treated as thermally identical to the offshore domain. It also illustrates the value of combining long-term regional products such as NOAA OISST v2.1 with higher-resolution coastal products such as Copernicus Marine SST fields[7][8].

6.2. Upwelling as a possible moderator of summer warming

The seasonal decomposition shows that warming is strongest in spring and weakest in summer. At point C, the summer trend is slightly negative. This result is consistent with a local moderating effect of seasonal upwelling. It does not prove that upwelling has intensified, but it indicates that nearshore summer SST does not simply follow the regional warming tendency. The coastal thermal regime is therefore likely shaped by the interaction between large-scale warming, local upwelling dynamics, coastal morphology and nearshore circulation.

6.3. Biological and ecological relevance of SST for Gelidium populations

The present study focuses on one environmental component only: sea surface temperature. It does not aim to provide a direct biological assessment of Gelidium beds in the El Jadida region, nor does it attempt to establish a causal relationship between SST variability and changes in local Gelidium biomass, cover, reproduction or harvesting yield. Such a causal interpretation would require in situ ecological monitoring, including repeated surveys of Gelidium abundance, population structure, recruitment, thallus condition, substrate characteristics, harvesting pressure and associated environmental variables. The objective of this work is more limited, but nevertheless relevant: to characterize the long-term marine thermal context in which Gelidium populations occur along an economically and ecologically important Moroccan Atlantic coastal sector.

The link between this SST analysis and Gelidium ecology is supported by several biological and ecological studies showing that Gelidium species are not indifferent to their thermal environment. The genus Gelidium includes perennial red algae attached to rocky substrates, whose persistence depends on the maintenance of suitable benthic habitats, vegetative propagation, regeneration and recruitment processes, as described in the biological synthesis of Santelices[4]. In the Atlantic context, Gelidium corneum is widely recognized as a valuable agarophyte and as a structurally important red seaweed associated with rocky coastal habitats, including the Atlantic coasts of Morocco, Portugal, Spain and France[1][3].

Temperature is particularly relevant because it can influence physiological and demographic processes in macroalgae, including growth, respiration, photosynthetic performance, reproduction, recruitment and recovery after disturbance. For Gelidium corneum, experimental evidence is especially important. Sainz-Villegas et al.[5] examined the combined effects of temperature and irradiance on vegetative propagation, including re-attachment capacity and the survival of re-attached fragments. Their results showed that both temperature and irradiance significantly affect the re-attachment process, with more favourable responses around 20 °C under low irradiance conditions, whereas less favourable thermal-light combinations may reduce the development of rhizoids and attachment structures. This demonstrates that temperature is not only a descriptive oceanographic variable, but a factor that may affect biological processes involved in the maintenance and regeneration of Gelidium populations.

The importance of considering SST is also supported by field-based studies from other north-eastern Atlantic regions. On the Basque coast, Borja et al.[9] reported a strong long-term decline of the canopy-forming alga Gelidium corneum, with biomass decreasing from approximately 12,000 t to 1,900 t over about two decades. The authors discussed several interacting environmental drivers, including sea surface temperature, wave climate, irradiance and nutrient availability. In the south-eastern Bay of Biscay, Muguerza et al.[10] also documented a large-scale decline in shallow rocky subtidal macroalgal biomass between 1982 and 2014. These studies do not imply that the same process is occurring in El Jadida, but they show that Gelidium beds and associated rocky-shore macroalgal communities can respond to long-term environmental changes.

Additional evidence comes from the Canary Islands. Alfonso et al.[11] reported major changes in the distribution of the endemic macroalga Gelidium canariense over recent decades, with more than 90% of its populations declining in Tenerife. The same study showed that the cover of Gelidium canariense and Gelidium arbuscula decreased significantly with increasing SST and air temperature. Although the ecological and biogeographic context of the Canary Islands differs from that of the Moroccan Atlantic coast, these results further support the relevance of thermal indicators when discussing the potential vulnerability of Gelidium species to climate-related change.

Therefore, the SST signal described for El Jadida should be interpreted as an environmental context indicator rather than direct biological evidence of Gelidium decline. The relatively weak summer warming at the coastal point C may reflect the moderating influence of local upwelling, which could partly buffer nearshore habitats during the warm season. However, the observed warming during spring and autumn remains ecologically relevant, because these transitional seasons may influence growth, recovery, reproductive timing, recruitment and competitive interactions within rocky-shore macroalgal communities. The response of Gelidium to future warming will likely depend on the interaction between SST, upwelling intensity, nutrient supply, irradiance, water movement, sedimentation, rocky substrate quality and harvesting pressure.

In this sense, the present study should be considered as a first thermal baseline for the El Jadida-Jorf Lasfar coastal sector. It provides a regional-scale assessment of the marine thermal signal over the period 1982-2025, while highlighting the need for future work combining satellite-derived SST, in situ temperature measurements and biological monitoring of Gelidium beds. This approach would allow future studies to move from thermal context analysis toward a more complete understanding of the ecological vulnerability and resilience of Moroccan Gelidium populations.

6.4. Comparison with Spain, Portugal and the Canary Islands

Comparison with the Iberian Peninsula and the Canary Islands is justified because Morocco, Portugal and Spain belong to the historical Atlantic Gelidium exploitation area for agar production. McHugh[1] identifies Morocco, Portugal and Spain among countries where harvested Gelidium has supplied local agar producers. Santos and Melo[2] also emphasized the importance and vulnerability of Gelidium resources in the global technical agar supply chain, particularly in relation to the shortage of technical agars and the need for careful resource management.

According to Borja et al.[9], the Basque coast of northern Spain experienced a marked decline of Gelidium corneum biomass, from about 12,000 t to 1,900 t over approximately two decades, with several environmental hypotheses including SST, wave conditions, irradiance and nutrient changes. Muguerza et al.[10] further documented long-term biomass loss in shallow rocky subtidal vegetation in the south-eastern Bay of Biscay, while Ramos et al.[12] described changes in the distribution of intertidal macroalgae along the northern coast of Spain. In the Canary Islands, Alfonso et al.[11] reported that more than 90% of populations of the endemic Gelidium canariense declined over three decades and that the cover of Gelidium species decreased significantly with increasing temperature. These examples do not demonstrate that the same trajectory is occurring in El Jadida, but they show that Gelidium-related issues in El Jadida should be considered within a broader Atlantic context of climate-related macroalgal change.

6.5. Limitations and monitoring needs

This study has several limitations. First, NOAA OISST is appropriate for long-term climate analysis but its 0.25° grid is coarse for nearshore ecological interpretation. Second, the Copernicus analysis presented here was limited to two months in 2025 and should be expanded to a full fine-scale time series. Third, SST alone cannot determine the ecological status of Gelidium populations. Field data on biomass, cover, recruitment, substrate condition, harvesting pressure, turbidity, nutrients, wave exposure and local upwelling indicators would be required to establish a robust ecological diagnosis.

Future work would benefit from combining satellite SST, in situ coastal temperature loggers, seasonal Gelidium surveys, upwelling indicators, nutrient measurements and harvest statistics. Such an integrated approach would make it possible to distinguish between climate-driven thermal change, local habitat degradation and direct exploitation pressure, while keeping the present analysis in its appropriate scope: a first thermal baseline based on SST.

7. Conclusion

The analysis of NOAA OISST data for 1982–2025 reveals a detectable warming signal in the El Jadida marine region, but the signal is spatially and seasonally heterogeneous. Annual warming is strongest at the near-offshore point D, intermediate at the offshore reference point B, and weakest at the coastal point C. Spring is the season with the strongest warming, whereas summer remains comparatively stable, especially near the coast. The slight negative summer trend at C is consistent with a moderating effect of coastal upwelling.

The complementary Copernicus extraction confirms a local gradient between the targeted coastal point and the offshore points, with C remaining cooler, especially in August 2025. These findings suggest that the El Jadida coastal sector cannot be interpreted as a simple continuation of the offshore thermal field. For Gelidium populations, the results provide an environmental context indicator, not a direct ecological diagnosis. The relevance of the SST analysis is nevertheless supported by biological and ecological studies showing that temperature, together with irradiance and other local factors, can affect Gelidium maintenance, regeneration and vulnerability. The work should therefore be viewed as a first climate-oriented assessment designed to support future field-based ecological studies.

Statements and Declarations

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Potential Competing Interests

The authors declare no competing interests. This statement should be confirmed before submission.

Ethics

This study did not involve human participants, animals, clinical data or experimental manipulation. Ethical approval was therefore not applicable.

Author contributions

Abdellatif ORBI: conceptualization, oceanographic interpretation, study design, writing, review and supervision. Jalal ANNACHAT: data extraction support, mapping/processing support and technical contribution. Both authors reviewed and approved the manuscript before submission. The exact CRediT roles and ORCID identifiers should be completed by the authors before final submission.

Data Availability

The SST data used in this study are publicly available from NOAA OISST v2.1[6] and the Copernicus Marine Service[8] product SST_ATL_SST_L4_REP_OBSERVATIONS_010_026. The processed monthly series, calculation sheets and scripts used for the tables and figures should be deposited in a public repository or made available upon reasonable request before final submission.

Use of Generative AI

Language editing, translation support and manuscript formatting assistance were supported by AI tools. The authors remain fully responsible for the scientific content, data interpretation, accuracy of results, references, and final manuscript.

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Declarations

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