

# Interannual Variability of Mediterranean Sea SST and Algerian Winter Rainfall

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## Abstract

This study examines how Algeria's winter (December-February, DJF) rainfall is affected by the trends and variability of the Mediterranean Sea Surface Temperature (SST) between 1993 and 2023. Empirical Orthogonal Function (EOF) analysis and composite diagnostics were used to identify dominant SST modes and their atmospheric linkages using high-resolution datasets (ERSST, CHIRPS, and NCEP/NCAR reanalysis). The second Mediterranean SST mode (EOF2), which is the main cause of rainfall variability in Algeria, accounts for 25.3% of the variance in SST and is distinguished by a zonal dipole (eastern cooling vs. western warming). The associated atmospheric patterns show that whereas cool phases reduce precipitation through anticyclonic conditions and subsidence, warm SST phases increase rainfall through cyclonic circulation, increased vertical motion, and moisture flux convergence. The study concludes that the interannual and annual variation of Mediterranean SST is one of the key regulators of the winter hydroclimate in Algeria, and it has important implications, for the variability of water resources in the region. The importance of interannual SST variability over long-term trends in regulating Algeria's winter hydroclimate is also highlighted by these findings, which are worth studying in the future.

## Keywords

Mediterranean SST, DJF Rainfall, Algeria, EOF Analysis, Atmospheric Circulation, Climate Variability, ENSO

## 1. Introduction

Providing more than 70% of the country's yearly precipitation in the northern

regions, where 90% of the population lives, winter (December-February, DJF) rainfall is essential to Algeria's agricultural output and water security (Meddi et al., 2010; Taïbi et al., 2019). Critical industries are supported by this seasonal rainfall, such as groundwater recharge for urban and rural water supply and rainfed agriculture, which produces 60% of Algeria's cereals (FAO, 2020). Socioeconomic stability is threatened by noted drops in DJF precipitation (15% - 20% since 2000) and an increase in the frequency of droughts (Kelley et al., 2023), which explains the value of comprehending its principal climatic causes, particularly on interannual scales.

In the past decades, the Mediterranean Sea has undergone significant warming, as well as an intensifying salinification process with consequences on the basin-scale density characteristics (Skiriris et al., 2024). While these long-term changes are critical, the interannual variability of Sea Surface Temperature (SST) is a more direct driver of seasonal climate anomalies. Regional variation has been associated with indices of atmospheric circulation, such as the Mediterranean Oscillation and ENSO, whereby the frequency of rainy days has been declining in the west and drought severity is generally on the rise (Tramblay et al., 2013; Taïbi et al., 2019). Although the North Atlantic Oscillation (NAO) has been a significant mode of winter hydroclimate in the Mediterranean region, its impact on the interannual variability of rainfall in Algeria is not as well established, particularly when viewed against a backdrop of warming in the Mediterranean (Lionello & Scarascia, 2020). The specific mechanisms connect the interannual variability of Mediterranean SST, including the relative power of sub-basin SST anomalies (zonal dipoles) compared to the basin-wide warming, to Algeria's winter.

Mediterranean SST anomalies have significant uncertainties, regarding the mechanisms by which the interannual variability of Mediterranean SST causes Algerian winter rainfall. To begin, numerous studies that have been conducted previously were based on coarse-resolution products of SST, which may blur localized air-to-sea interaction processes that are important to the variability of North African climates (Darmaraki et al., 2019).

Second, the relative contribution of the circulation dynamics and thermodynamic feedbacks, e.g., improved moisture availability, to mediating the rainfall response to interannual SST changes, is a subject of ongoing debate (Tuel & Eltaïhir, 2020).

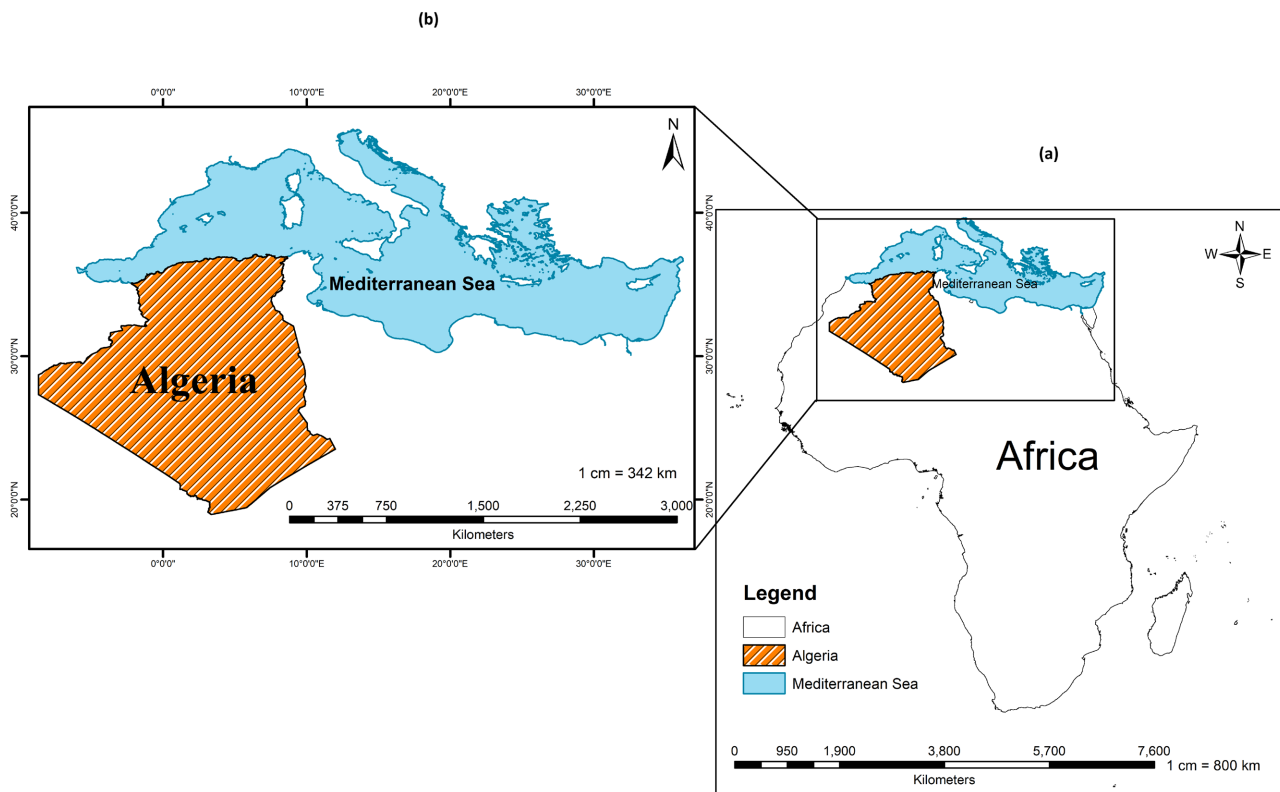
Third, however much Mediterranean hydroclimate is generally known to be driven by large-scale teleconnections (e.g., ENSO and, to a lesser degree, NAO), there is little empirical evidence that these connections interact with Mediterranean SSTs to drive Algerian rainfall (Lionello & Scarascia, 2020). These loopholes limit predictive ability and make proper planning to manage water resources under climatic change difficult.

In order to overcome these issues, this work combines atmospheric reanalysis (NCEP/NCAR; Kalnay et al., 1996), high-resolution SST (ERSST; Huang et al.,

2017), and rainfall (CHIRPS; Funk et al., 2015) data between the years 1993 and 2023. The objectives are to: Describe the spatiotemporal variability of Mediterranean SST and Algerian DJF rainfall in terms of empirical orthogonal function (EOF) analysis and trend diagnostics (Xoplaki et al., 2004). Determine the atmospheric mechanisms that relate the variability of rainfall to SST variability using composites of circulation fields such as sea-level pressure and vertical velocity and moisture flux (Sein et al., 2014). Evaluate the changes in these linkages due to major drivers like regional SST dipoles, ENSO, and NAO (Comas-Bru et al., 2023; Lionello & Scarascia, 2020). These methods together make this work the first effort to evaluate the impact of coupled ocean-atmosphere systems in explaining the variation in Algerian winter rainfall in response to interannual Mediterranean SST variability. The results also point to possibly predictable factors of rainfall variability, providing information that can be directly applied in climate adaptation planning in water-deficient areas.

## 2. The Domain of Study

Algeria is a large state in Africa with an area of 2,381,741 Km<sup>2</sup>, and is situated in North Africa, between 19° N and 37° N, and 9° W and 12° E (World Bank, 2022). The geographical context of the study area is shown in Figure 1, which illustrates



**Figure 1.** Geographical context of the study area (a) The position of Algeria within North Africa. (b) The specific study domains: the Mediterranean Sea basin (blue shading), defined as the oceanic domain for Sea Surface Temperature (SST) analysis, and northern Algeria (green shading), defined as the terrestrial domain for precipitation analysis.

(a) the position of Algeria within North Africa and (b) the specific study domain. The length of its northern Mediterranean coastline reaches about 1622 km, and the southern area is also composed of large areas of the Sahara Desert that extend over 80 percent of the national territory (ISS African Futures, n.d.; Ministry of Foreign Affairs of Algeria, n.d.). Such a geographic structure results in significant climatic disparity, with the northern parts of the coastlines and Tell Atlas Mountains enjoying a Mediterranean climate of mild and wet winters and hot and dry summers, but the south shows hyper-arid Saharan characteristics (ONS, 2023; Peel et al., 2007). The overwhelming majority of Algeria's population, exceeding 45 million people, has been concentrated in the northern Mediterranean, where agriculture, water resources, and large cities, including Algiers, Oran, and Constantine, are located (ONS, 2023).

In Northern Algeria, it is especially reliant on winter (DJF) precipitation, which provides the majority of annual precipitation needed for freshwater supply and agricultural output (Meddi et al., 2010; Belala et al., 2018). What defines this rainfall regime is the Mediterranean Sea that borders North Algeria. Fluctuations in Mediterranean sea surface temperatures (SSTs) directly affect the regional atmospheric circulation, transport of moisture, and cyclones and have strong control over the outcome of precipitation (Lionello & Scarascia, 2020).

Mass circulation patterns like the North Atlantic Oscillation (NAO) further contribute to variability in rainfall; negative NAO phases are typically associated with warmer winters in northern Algeria (Achite et al., 2022). Recent evaluations point to the growing aridity and rising rainfall uncertainty in North Africa, which shows that Algeria is exposed to climate change (IPCC, 2023). Algeria, being a very distinctive place between the Mediterranean and Sahara interface, has climatic conditions that are extremely susceptible to intertwined ocean-atmosphere mechanisms. Based on this, the study area, which includes the Mediterranean Sea and northern Algeria as defined in Figure 1, is critical in the research to examine the variable patterns variability of winter SSTs and their impact on the December–February rainfall in Algeria. Understanding these linkages can be important to enhance predictive ability and inform climate adaptation efforts in a water-limited area.

### 3. Data Sources and Methods

The relationship between Mediterranean Sea surface temperature (SST) fluctuations and winter rainfall over Algeria from 1993 to 2023 is examined in this work utilizing a multi-source dataset that combines observational, reanalysis, and satellite-derived data. The Extended Reconstructed Sea Surface Temperature (ERSST v3b) dataset, provided by NOAA's National Centers for Environmental Information, was used to obtain monthly SST anomalies. With a resolution of  $2.0^\circ \times 2.0^\circ$ , this dataset provides global coverage and combines in situ and satellite observations to create a gap-free SST product that is ideal for long-term climate research. Wind fields, vertical velocity at 500 hPa, sea level pressure, velocity poten-

tial at 200 hPa, relative humidity, and vertically integrated moisture flux were among the atmospheric circulation variables obtained from the NCEP/NCAR Re-analysis dataset at a resolution of  $2.5^\circ \times 2.5^\circ$ .

These factors help define the physical processes that connect changes in sea surface temperature to changes in rainfall. We obtained the precipitation data from the CHIRPS v2.0 product, which provides daily rainfall estimates with a resolution of  $0.05^\circ \times 0.05^\circ$  based on satellite infrared data and station observations. The CHIRPS dataset is very effective at showing how rainfall changes across Algeria's complex terrain, especially in the Tell Atlas area.

After eliminating linear trends to isolate interannual variability, DJF Mediterranean SST anomalies were subjected to Empirical Orthogonal Function (EOF) analysis to investigate SST variability and its relationship to atmospheric dynamics. SST fields are broken down using this method into orthogonal spatial modes and related temporal patterns (principal components), where dominant variability structures are represented by the leading modes. North's rule of thumb and Monte Carlo resampling were used to test statistical robustness. The atmospheric responses during winters with anomalously warm or cool Mediterranean SSTs (defined as  $\pm 1$  standard deviation from the mean) were then investigated using composite analysis.

Key atmospheric indicators analyzed include vertical motion (omega at 500 hPa), relative humidity at 850 hPa, meridional winds at 700 hPa, and velocity potential at 200 hPa, alongside vertically integrated moisture flux between 1000 and 300 hPa using the Trenberth (1991) formulation. Significance testing was performed via two-tailed t-tests and Monte Carlo field significance analysis to ensure the reliability of spatial patterns. Full methodological equations and implementation details are provided in the Supplementary Materials.

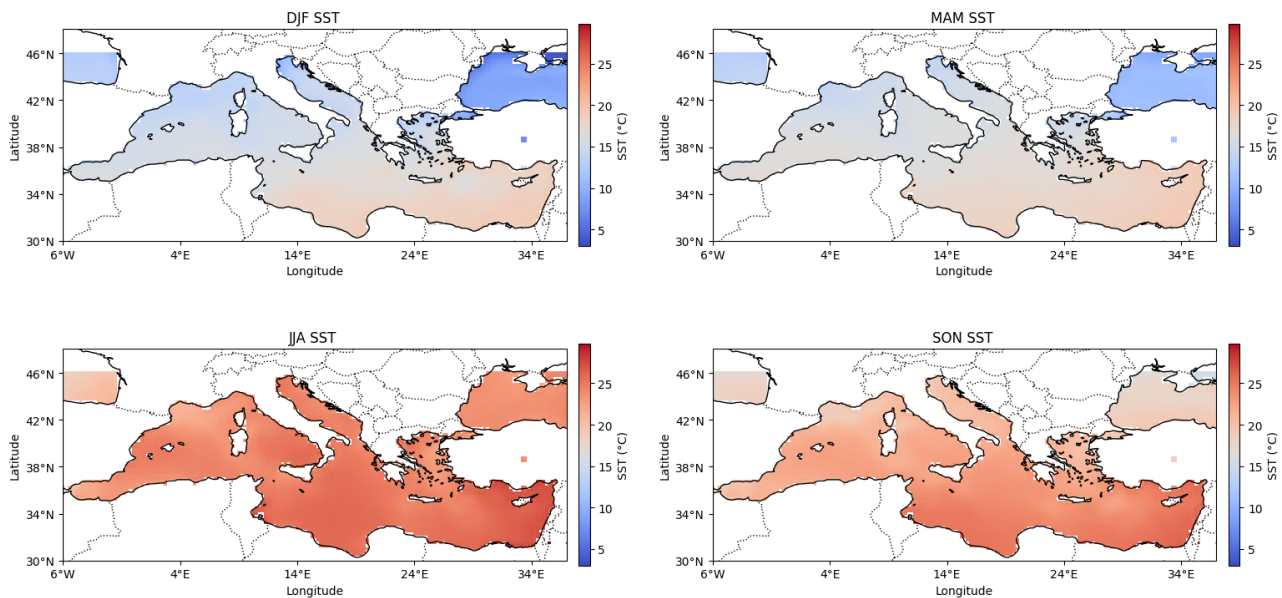
EOF and composite analyses form a complementary framework; EOF analysis identifies the leading modes of SST variability across the Mediterranean basin, while composite analysis reveals the atmospheric mechanisms through which these SST anomalies influence Algerian rainfall. This dual approach enables a robust examination of the ocean-atmosphere-land interactions driving winter precipitation variability, supporting a broader understanding of climate dynamics in the African region.

## 4. Results and Discussion

### 4.1. Variation of SST

#### 4.1.1. Climatology

The Mediterranean has clear seasonal thermal regimes (Figure 2) that crucially condition air-sea interactions controlling the variability of rainfall in Algeria during December-February (Jordà et al., 2017). As a result of continental effects, winter (DJF) is characterized by a strong north-south SST gradient ( $12^\circ\text{C} - 18^\circ\text{C}$ ) with the coldest water in the northern basins; autumn (SON) is characterized by high coastal SSTs along North Africa, with higher Algerian waters  $2^\circ\text{C} - 3^\circ\text{C}$



**Figure 2.** The spatial distribution of seasonal variations in Sea Surface Temperature (SST) in the Mediterranean Sea: (a) DJF; (b) MAM; (c) JJA, and (d) SON from 1993 to 2023.

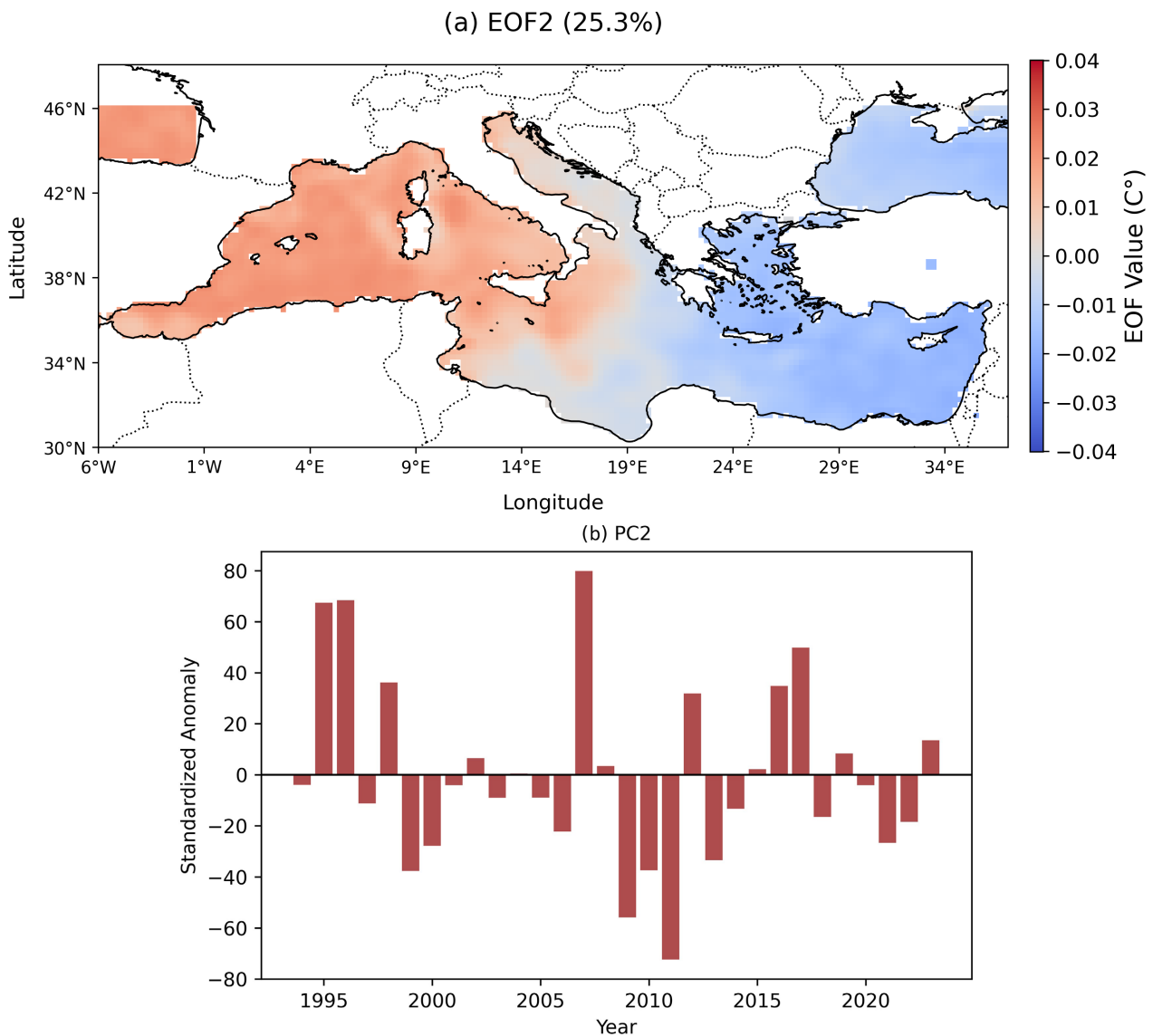
warmer, enhancing the availability of early-winter moisture and latent heat fluxes. Summer (JJA) is characterized by high temperatures (24°C - 30°C) in the eastern Levantine Basin sustained by seasonal heat storage, and spring (MAM) by the quick development of western fronts and eastward-moving thermal gradients. These reversing N-S (winter) and E-W (summer) thermal variations form thermal contrasts that are capable of altering low-level baroclinicity and impacting the development of weather systems affecting Algeria (Lionello et al., 2014).

The comparatively warmer western Mediterranean SST also increases evaporation that may amplify the hydrological cycle, which in turn alters the trajectory of Mediterranean cyclones contributing rainfall to Algeria, with the patterns also being further modulated by large-scale climate modes like the NAO on a background of accelerated basin-wide warming (Pastor et al., 2020).

#### 4.1.2. Leading Modes of Interannual Variation

The second EOF mode (EOF2) represents a strong zonal dipole pattern (explaining 25.3% of the variability in Mediterranean winter SST) (Figure 3(a)). Unlike the basin-wide warming observed by EOF1, the pattern presents conflicting anomalies between the eastern basin (negative) and the western/central Mediterranean (positive), which are maximum along the coast of Algeria.

It exhibits strong interannual variation with no significant trend in the associated principal component (PC2; Figure 3(b)), with strong extremes in 2007 (+1.8) and the strongest negative in 2010 (-1.6). This dipole is likely due to the redistribution of heat under wind shear, but with a large-scale circulation, which is supported by a significant correlation between these changes and NAO indices ( $r = 0.65$ ,  $p < 0.01$ ). This pattern plays a vital role in Algerian precipitation, with the positive SST anomalies along the coastline stimulating local evaporation and



**Figure 3.** EOF2 mode of Mediterranean SST for December-February (1993-2023). (a) Spatial pattern of EOF2, explaining 25.3% of the total variance. (b) Corresponding PC2 time series, showing standardized SST dipole anomalies from 1994 to 2023. These alternating phases highlight interannual variability.

low-level instability, which would favor more severe convective precipitation events during the winter period (Lionello et al., 2014; Jordà et al., 2017).

The adverse NAO phase, which usually accompanies the positive phase of this SST dipole, favors cyclonic paths of activity and moisture transport to the North African region and thus enhances the chances of excessive precipitation in the area (Dünkeloh & Jacobeit, 2003).

The composite analysis was done based on typically warm and cold years of the Mediterranean SST using the normal Principal Component 2 (PC2) time series, which is computed in accordance with the EOF analysis. Warm years were those in which the PC2 value had a normalized value that exceeded the standard deviation of +0.5, whereas the cool years were those in which the PC2 value had a nor-

malized value that was below the standard deviation of  $-0.5$ . The years that gave the contrasting cases in the composite analysis of atmospheric circulation and associated patterns can be found in the positive phase of the dipole [1995, 1996, 1998, 2002, 2007, 2008, 2012, 2015, 2016, 2017, 2019 and 2023] and the negative phase [1994, 1997, 1999, 2000, 2001, 2003, 2005, 2006, 2009, 2010, 2011, 2013, 2014, 2018, 2020, 2021, and 2022] according to the warm and cool years.

#### 4.2. Interannual Variation of Mediterranean Warm-Cool SST Phases

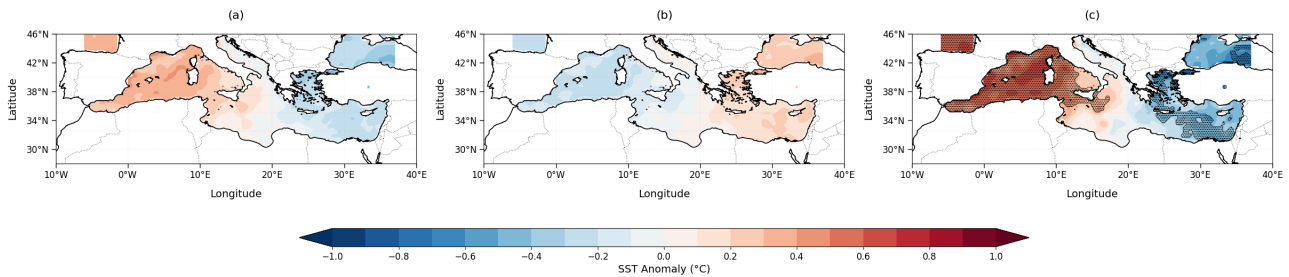
The effect of interannual variability of the Mediterranean Sea Surface Temperature (SST) on Algerian winter (DJF) rainfall and the preponderant mode of co-varying variability are examined in this section. The analysis is based on the EOF findings whereby mode two (EOF2) was classified as a dipole pattern of zonal SST that is of paramount importance to rainfall variability. In contrast to the first mode (EOF1), which reflects mostly the basin-wide trend of warming and has a weak relationship with precipitation, EOF2 reflects the spatially heterogeneous anomalies that are the direct causes of atmospheric circulation. The uniform spatial pattern of EOF1 provides a weak forcing for altering regional wind and pressure patterns, whereas the strong thermal gradients of the EOF2 dipole efficiently force cyclonic/anticyclonic circulation anomalies that directly control moisture transport and vertical motion.

The Principal Component (PC2) correspondingly has a high interannual variation and no significant long-term trend, and thus it provides an ideal basis for defining the typical warm and cool SST phases. The combination of such phases is thus employed in probing the unique ocean-atmosphere dynamics and their direct effect on rainfall patterns in Algeria.

#### Spatial Patterns of Mediterranean SST Anomalies during Warm and Cool Phases

The composite study of the winter SST in the Mediterranean shows that there are clear spatial distribution patterns that distinguish the warm and cold phases and that have pivotal implications for the variability of rainfall in Algeria.

On warm years (**Figure 4(a)**), positive SST anomalies greater than  $+0.5^{\circ}\text{C}$  are observed throughout the entire basin, with the strongest warming ( $+0.8^{\circ}\text{C}$  to  $+1.0^{\circ}\text{C}$ ) in the western Mediterranean and the Algerian Basin, the region of the most vital moisture source for North African precipitation. On the other hand, the cool years (**Figure 4(b)**) show general negative anomalies, especially robust in the central and eastern Mediterranean ( $-0.6^{\circ}\text{C}$  to  $-0.8^{\circ}\text{C}$ ). The difference map (**Figure 4(c)**) shows statistically significant warming characteristics ( $p < 0.05$ ) in the western Mediterranean, the Algerian coastal sector included, where the SST deviation in warm years is estimated at  $+0.7^{\circ}\text{C}$  above the average value in cool years. This local climate change increases latent heat transport and moisture levels in the atmosphere, which may increase the hydrological cycle along the coast of the North African region (Jordà et al., 2017).



**Figure 4.** Anomaly composites of winter (DJF) SST for warm years, cool years, and their difference (warm minus cool). The stippling in (c) indicates statistically significant variance within the 95% confidence interval (two-sample t-test).

It has a spatial arrangement that implies the western Mediterranean warming, as opposed to the basin-wide SST enhancement, can be especially effective in changing anticyclones and moisture transport pathways to Algeria (Lionello et al., 2014).

The warm/cool cycles here are associated with familiar climate modes such as the positive/negative phases of the North Atlantic Oscillation, which vary wind patterns and the redistribution of heat across the Mediterranean (Dünkeloh & Jacobeit, 2003).

This positive phase concentration of substantial warming in the Algerian Basin makes a mechanistic connection between Mediterranean SST variability and the interannual variation of the Algerian winter precipitation observed in earlier evaluations (Merniz et al., 2019a, 2019b).

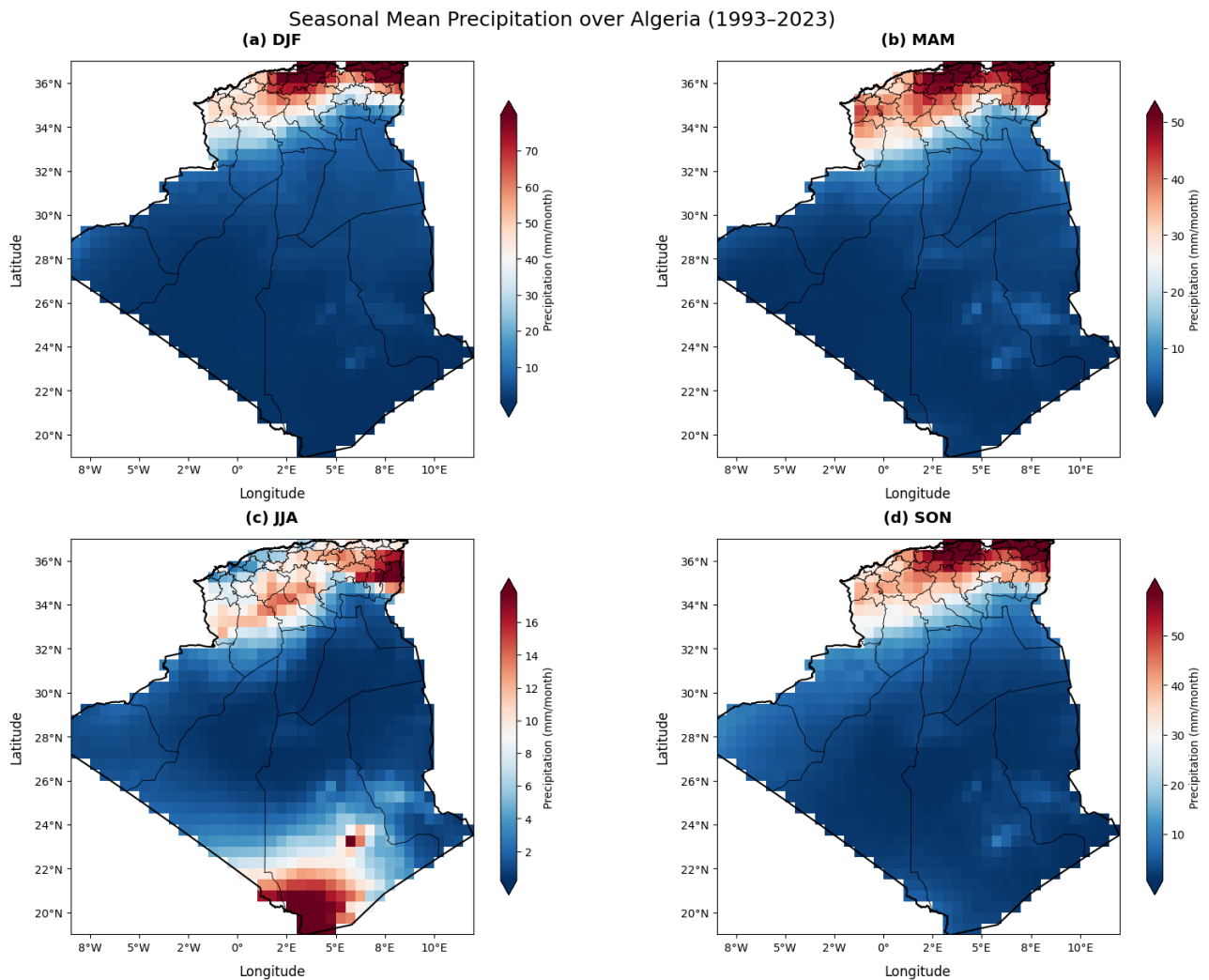
Such combined analysis therefore identifies the existence of unique Mediterranean SST regimes that lead to and possibly control the rainfall extremes essential to Algerian water resources and agricultural planning.

### 4.3. Variation in Rainfall

#### 4.3.1. Spatial Distribution of Rainfall

As the country has diverse climatic regions, the precipitation climatology of Algeria (Figure 5) between 1993 and 2023 exhibits a high degree of north-south gradient and seasonality, which is dictated by its location in the Mediterranean-Saharan transition zone (Merniz et al., 2019b). Winter (DJF) brings the highest amount of rain (>70 mm/month) to the northern coast and Tell Atlas, which is nourished by Mediterranean anticyclones, with the Saharan south being hyper-arid (<10 mm/month).

There is a response of a 20% - 30% decrease in spring (MAM) after storm tracks have moved away, a 100% dry summer (JJA) except for monsoonal intrusion in the Hoggar, and the entry of the wet season in the north in autumn (SON). This distribution in space and time, with more than 90% of the renewable water resources of the country being in the north (Sahnoune et al., 2013), is explicitly connected to the patterns of the Mediterranean sea surface temperatures that regulate the availability of moisture and storm paths. As a result, interannual winter Mediterranean SST is a vital influence on the rainfall that predetermines the water security and agricultural performance of Algeria (Lionello et al., 2014; Merniz et al., 2019b).

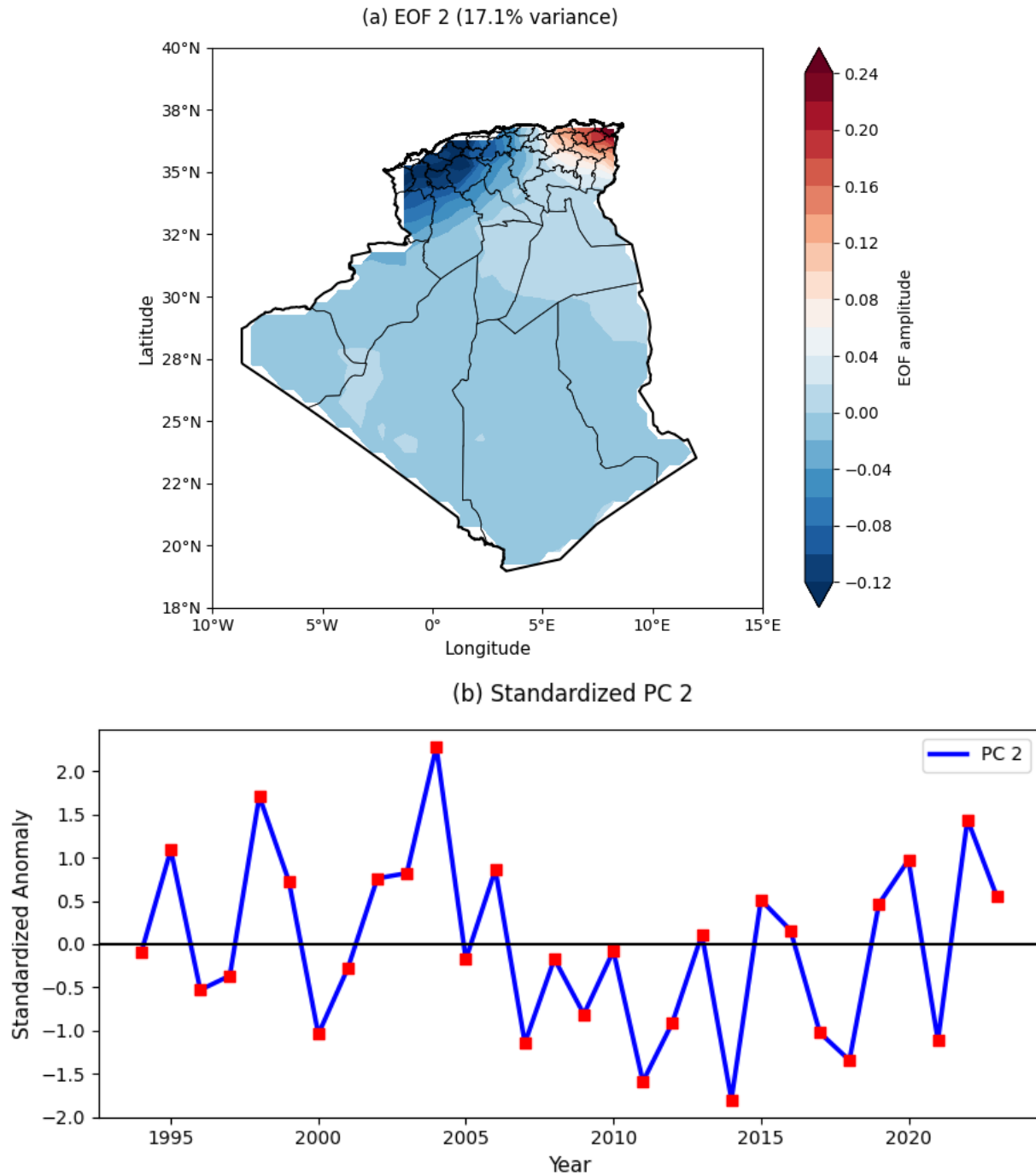


**Figure 5.** The spatial distribution of the seasonal mean precipitation over Algeria from 1993 to 2023, for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON).

#### 4.3.2. Leading Modes of Interannual Variation

A pronounced northeast/north-central dipole pattern is revealed by the second precipitation mode (EOF2), which accounts for 17.1% of the variability in winter rainfall over Algeria (**Figure 6(a)**). Kabylie and Annaba (+0.4 - 0.6) and Mitidja and Chelif basin (-0.3 - 0.5) are found to have strong positive loading and negative values respectively, whereas southern Algeria is not affected. The related PC2 time series (**Figure 6(b)**) indicates considerable interannual variation with negative phases (e.g., 2009, 2011) reversing the gradient and positive phases (e.g., 2002, 2006, 2022) doubling northeastern precipitation relative to north-central areas.

As the positive phase is associated with stronger north-easterly flow over the central Mediterranean, the given dipole pattern is the most likely response of the region to the passing of storms and movement of moisture. The fact that the pattern persisted in the 1993-2023 period of the research and no trend was observed ( $p > 0.05$ ) shows that the pattern is a fundamental type of winter climate variability in northern Algeria.



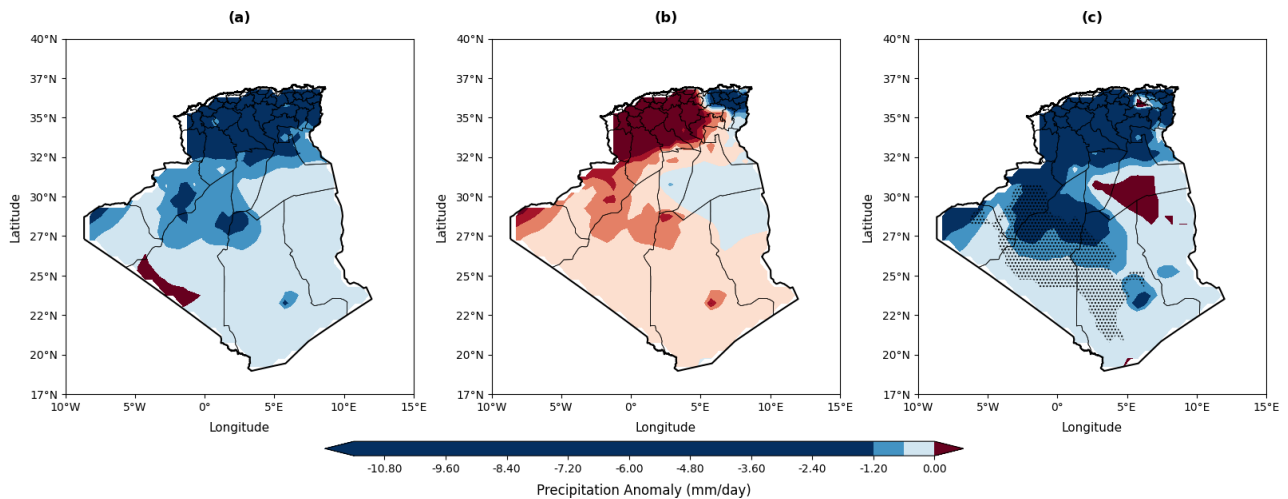
**Figure 6.** (a) Second Empirical Orthogonal Function (EOF2) of Algeria (DJF) precipitation anomaly (1993-2023), which explains 17.1% of the all-time variance. (b) Standardized Principal Component (PC2) time series of interannual variations in the strength of the EOF2 pattern.

#### 4.3.3. Algerian Rainfall Response to SST Phases

The composite analysis of precipitation anomalies during extreme EOF2 phases reveals a strong teleconnection between Mediterranean SST and Algerian rainfall (**Figure 7**).

This is consistent with known processes in which warm Mediterranean SSTs

enhance low-level moisture convergence along the Algerian coast, resulting in considerably higher atmospheric moisture during warm PC2 years (**Figure 7(a)**). The precipitation anomalies in the Tell Atlas area, exceeding +10 mm/day, are linked to processes that generate extreme rainfall events and influence long-term streamflow in northern Algeria's basins (Benaini et al., 2023; Hallouz et al., 2019).



**Figure 7.** The composite of DJF precipitation anomalies (mm/day) over Algeria during warm and cool Mediterranean SST years from 1993 to 2023. (a) During warm years, (b) during cool years, (c) difference between warm and cool years, highlighting statistically significant differences ( $p < 0.05$ ) are indicated by stippling.

Conversely, cool PC2 phases (**Figure 7(b)**), associated with a strengthened and westward-displaced Mediterranean ridge, lead to widespread drying caused by anomalous subsidence and suppressed convection. The most pronounced negative anomalies (around  $-10$  mm/day) occur in the agriculturally sensitive Chelif Basin.

This region's documented vulnerability to precipitation variability, combined with future projections under climate change, underscores the severity of such dry periods (Hallouz et al., 2019; Hamitouche et al., 2024). The difference map (**Figure 7(c)**) shows statistically significant ( $p < 0.05$ ) wetter conditions during warm phases, with the most substantial differences ( $\Delta > 5$  mm/day) observed in the northwestern agricultural regions. These rainfall anomalies are dynamically consistent with SST-driven circulation changes; warm periods favor enhanced westerly flow and orographic uplift against the Tell Atlas, while cool periods promote large-scale subsidence. These mechanisms are critical for understanding the projected increase in both extreme precipitation and drought frequency across Algeria's sub-regions (Hamitouche et al., 2024), highlighting the key role of Mediterranean SST variability as a primary modulator of the Algerian winter hydroclimate.

These findings have direct implications for seasonal forecasting, providing a dynamical foundation to support water resource management for dams in northern Algeria and to inform agricultural planning. This enhanced understanding is

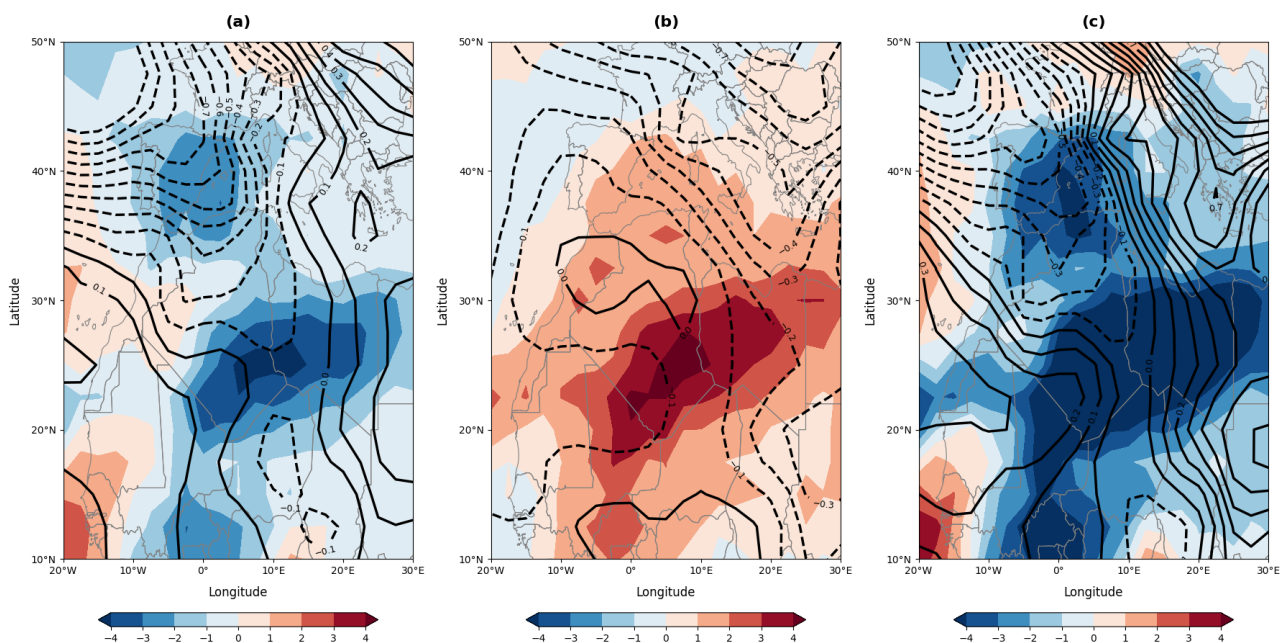
crucial for interpreting observed trends and future projections of hydrological extremes in the area.

#### 4.4. The Mechanisms of DJF SST on Circulation

This section diagnoses the large-scale atmospheric response to Mediterranean SST anomalies by exploring winter (DJF) circulation anomalies using composite analysis of PC2 extremes.

##### 4.4.1. Circulation (SLP) and Convective (OLR) Response to SST Phases

The composite results of Outgoing Longwave Radiation (OLR) and Sea Level Pressure (SLP) (**Figure 8**) shows a direct atmospheric pathway in which interannual variability in Mediterranean SST controls winter rainfall in Algeria. This physical process is based on the ocean-atmosphere interaction, initiating with heat and moisture exchange at the sea surface.



**Figure 8.** Outgoing Longwave Radiation (OLR, shading;  $W/m^2$ ) and Sea Level Pressure (SLP, contours; hPa) for (a) warm years, (b) cool years, and (c) their difference, during DJF from 1993 to 2023.

During warm Mediterranean SST phases (**Figure 8(a)**), the sea surface becomes a heat engine that warms the marine surface layer and increases air buoyancy. This leads to convection and results in a strong cyclonic anomaly over the western Mediterranean basin, characterized by a sea level pressure deficit up to  $-1.5$  hPa.

This cyclonic circulation impacts directly the local hydroclimate through two mechanisms. First, it enhances low-level westerly moisture transport toward Algeria. Second, concurrent warm SSTs fuel the atmosphere through increased evaporation, enriching the moisture content of the advected air masses. When this warm, moist air is transported landward and undergoes orographic lifting, the water vapor condenses and the resultant latent heat increases the energy of the

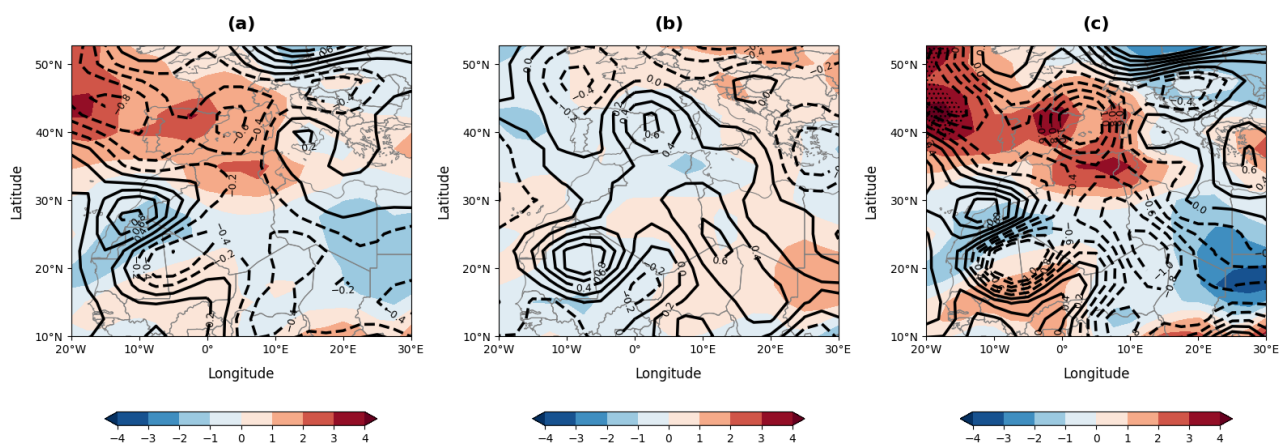
system. A major consequence is an escalation of convective activity, which is indicated by large negative anomalies of Outgoing Longwave Radiation (OLR) of up to  $-12 \text{ W m}^{-1}$  ( $p < 0.01$ ), leads to excessive precipitation across northern Algeria.

Conversely, cool and Mediterranean SSTs (**Figure 8(b)**) establish an anticyclonic regime, characterized by a positive SLP anomaly of  $+1.2 \text{ hPa}$ . The transfer of heat and moisture is suppressed by the cool sea surface, which stabilizes the atmosphere as well as promotes subsidence. This area, a high-pressure system, is also active in discouraging convection and enhancing dry conditions, evidenced by positive OLR anomalies of over  $+8 \text{ W m}^{-2}$ .

The contrast between these two phases is sharp (**Figure 8(c)**), exhibiting an SLP gradient of more than  $2.5 \text{ hPa}$ , and an OLR difference as large as  $-20 \text{ W m}^{-2}$  in the northwestern part of Algeria. Warm SST phases statistically describe a considerable amount of rainfall variance ( $r^2 = 0.68$ ). The physical basis of seasonal predictability is that there is a strong SST-convection relationship that is based on these thermodynamic mechanisms. According to operational forecasters, however, these local SST signals are damped or overridden by those of large-scale circulatory variability such as the North Atlantic Oscillation (NAO), which complicates seasonal forecasts (MedCOF, 2023). Learning about this SST to circulation to rainfall cascade is now becoming more important for climate adaptation in Algeria, where droughts are expected to occur because of warming in the Mediterranean (Zittis, 2022).

#### 4.4.2. Mid-Tropospheric Humidity and Vertical Velocity

An analysis of the 700 hPa level explains how the thermodynamic and dynamic processes by which Mediterranean SST phases regulate Algerian winter rainfall can be described and gives a mid-tropospheric perspective of the SST-driven response. The relative humidity and vertical velocity (omega) composite anomalies, as shown in **Figure 9**, show a drastic difference between the warm and cool phases, which are directly related to the ocean surface features and atmospheric processes that control precipitation.



**Figure 9.** Composite anomalies of DJF relative humidity (shading, in %) and omega (arrows, in m/s) at 700 hPa during (a) warm years, (b) cool years, and (c) their difference from 1993 to 2023 over Algeria.

When the sea is warm into a sea surface temperature (SST), the sea surface serves as an intense heat and moisture source. The increased evaporation causes the water to be pumped into the atmosphere, which is carried by the cyclonic circulation. This leads to the invasion of wet, oceanic air and high relative humidity anomalies, above +15 percent to +20 percent ( $p = 0.01$ ) in northern Algeria, as visualized in the warm-year composites of **Figure 9(a)**. At the same time, the surface heating and latent heat release from the clouds cause the air mass to be buoyant, thus causing a strong vertical movement of the air with omega anomalies of up to  $-0.12 \text{ Pa s}^{-1}$ . This rich supply of moisture (the fuel) and sustained lift (the engine) ensures a highly conducive environment for the development and intensification of precipitation, especially by the orographic forcing on the windward sides of the Tell Atlas.

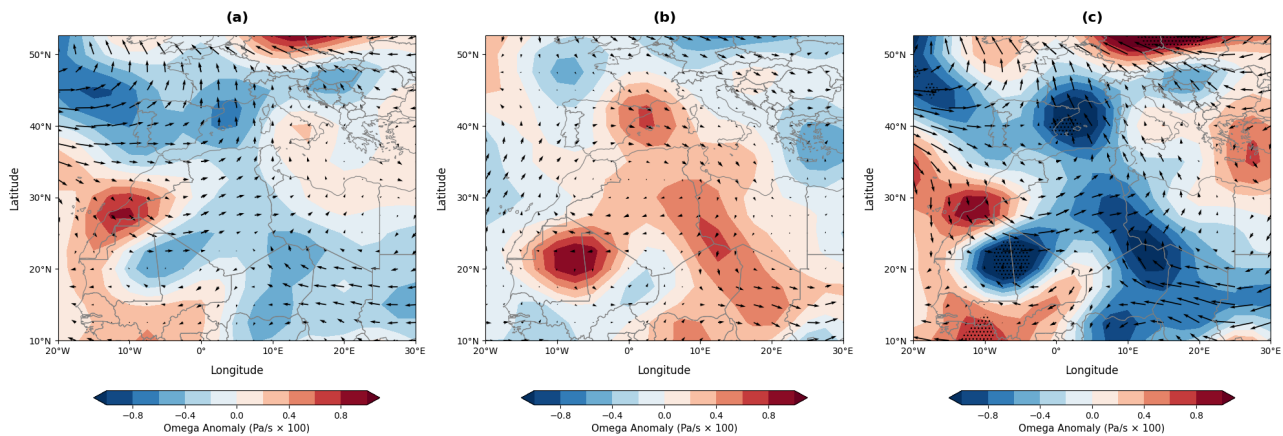
On the other hand, when the SST is cool, the energy transmission is suppressed by the ocean surface. The reduced water loss is due to drier air masses, which is related to negative relative humidity anomalies between  $-12$  and  $-18$ , illustrated in **Figure 9(b)**. The stabilized atmosphere is also a feature of the cool surface, which encourages high levels of subsidence as denoted by positive omega anomalies of  $+0.09 \text{ Pa s}^{-1}$ . This circulation pattern has been observed to actively suppress rainfall due to adiabatic warming in the atmosphere caused by compression and the reduced availability of moisture. The compounding effect of large-scale subsidence and rain-shadow effects is demonstrated by the most severe drying of  $-22\%$  in places such as the Chelif Basin.

These stages shown in **Figure 9(c)** differ dramatically with a relative humidity gradient (-RH) of up to  $+35\%$  and a vertical velocity gradient ( $-0.21 \text{ Pa s}^{-1}$ ) of  $-0.01$  ( $p < 0.01$ ). These steepest contrasts are consistent with the Atlas topography, which proves the contribution of orography to SST-forced signal enhancement. These thermodynamic (moisture availability) and dynamic (vertical motion) causes of change are collectively attributed to a significant part of the observed variation in winter precipitation ( $r^2 = 0.76$ ). This is becoming more critical in the Mediterranean, which is a well-known hotspot of climate change, warming at a higher rate than the average global climate, worsening the hydrological cycle (Cusack & Cox, 2024; IPCC, 2021). The results yield an objective basis for the seasonal projections and emphasize the dominant role of Mediterranean SST in determining the winter hydroclimate of Algeria in a warming world.

#### 4.4.3. Low-Level Circulation and Vertical Motion

A strong correlation between Mediterranean SST anomalies and North African winter dynamics is revealed by the examination of 850 hPa circulation patterns (**Figure 10**).

In warm SST conditions (**Figure 10(a)**), the cyclonic circulation caused by heat builds a pattern of onshore westerly winds (maximum anomaly of  $+3.2 \text{ m/s}$ ). This circulation accomplishes two very important tasks: it moves wet marine air to the interior, and it causes an abundance of convergence at the surface, which causes air to rise. This is supported by high upward movements (negative omega anomalies, e.g.,  $-0.15 \text{ Pa s}^{-1}$ ).



**Figure 10.** Composite of 850 hPa vertical velocity (omega; blue contours, Pa/s) and wind vectors (m/s) during DJF for (a) warm years, (b) cool years, and (c) their difference (warm minus cool) over the period 1993-2023.

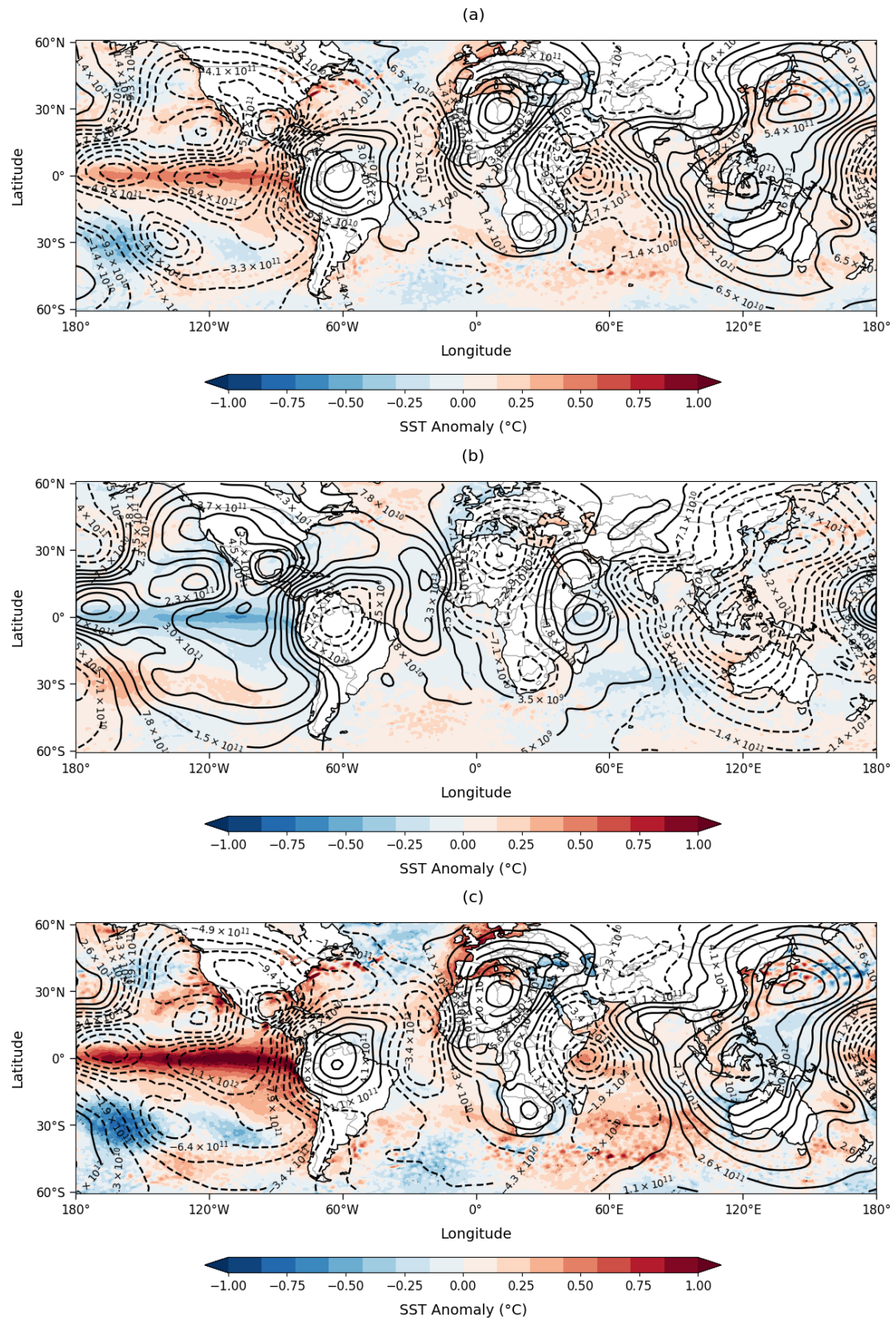
A forced ascent coupled with orographic lift against the Tell Atlas mountains increases upward movement by 30 - 40 percent, providing optimum precipitation growth conditions. On the other hand, in cool SST periods (**Figure 10(b)**), the anticyclonic regime generates subsidence ( $+0.10 \text{ Pa s}^{-1}$ ) and offshore or weaker winds. This trend actively suppresses rainfall, which suppresses the ascent, instills atmospheric stability, and decreases moisture advection in the Mediterranean. These phases (**Figure 10(c)**) are drastic and a sharp contrast in the vertical velocity ( $-0.25 \text{ Pa s}^{-1}$ ) shows the power of the SST forcing. These dynamic factors including SST are associated with a significant part of the interannual rainfall variance in Algeria ( $r^2 = 0.79$ ). This process is supported by a stronger land-sea thermal gradient ( $\Delta T \approx +1.8^\circ\text{C}$ ) during warm intervals, which increases the intensity of the onshore movement and moisture transfer even more. The findings support the role of the Mediterranean as a primary moisture source due to positive SST-rainfall teleconnections in the Maghreb, which are already understood (Taïbi et al., 2022).

Moreover, the process of increasing this dynamic pathway can be more dangerous due to the fact that the Mediterranean warms more quickly than the global average (Pastor et al., 2024), which means that the increasing risk of hydroclimatic extremes in Algeria is more dependent on Mediterranean SST as a significant variable in seasonal forecasting and climate adaptation (Hamitouche et al., 2024).

#### 4.5. VPT and SST global

In order to understand the controlling processes of Sea Surface Temperature (SST) patterns in the Mediterranean Sea, a study of global atmospheric circulation is necessary. It is found in this inquiry that massive climate processes that begin in remote ocean basins are the ultimate determinants of regional ocean warming and cooling, which in turn influences winter variability of rainfall in North Africa.

As indicated in **Figure 11**, the determining factors of the patterns of the Sea Surface Temperature (SST) in the Mediterranean Sea are greatly influenced by global atmospheric circulation, and among these factors, El Niño-Southern



**Figure 11.** The composite of SST anomalies (shaded, in °C) and velocity potential (VPT) anomalies at 200 hPa (contours; units:  $10^6 \text{ m}^2/\text{s}$ ) during DJF for (a) warm years, (b) cool years, and (c) the difference between warm and cool years from 1993 to 2023.

Oscillation (ENSO) stands out. This indicates that the major determinants of the regional Mediterranean SST dipole (EOF2), which, in turn, controls the variability of winter rainfall in North Africa, include large-scale climate patterns of tropical Pacific origin. The composite analysis also shows a strong teleconnection. **Figure 11(a)** indicates that El Niño events in the tropical Pacific are always accompanied by warm phases of the Mediterranean SST dipole, which are characterized by an SST anomaly of above  $+0.8^{\circ}\text{C}$  in the Niño 3.4 region. Such a correlation is mediated in place by a well-known pathway of atmospheric processes where the warm SSTs in the central/eastern Pacific serve as a giant heat engine, eliciting heavy convection and upper-level diversion. This separation, which is manifested in the velocity potential anomalies, stimulates a standing Rossby wave train that travels to the mid-latitudes and eventually propagates the cyclonic circulation, typical of the warm phase of the EOF2 mode in the Mediterranean (Cai et al., 2020). On the other hand, **Figure 11(b)** shows that cool periods of the Mediterranean dipole are highly associated with La Niña conditions in the Pacific. Cool SST anomalies in the tropical Pacific lead to the creation of a changed atmospheric wave train that favors anticyclonic conditions and the typical eastern warming/western cooling pattern of the cool EOF2 phase in the Mediterranean. **Figure 11(c)** in the difference map shows the vast difference between the two phases, indicating a  $2.0^{\circ}\text{C}$  Pacific SST gradient and considerable variations in the upper-level atmospheric circulation across the Mediterranean basin. These distant tropical forcings can quantitatively account, by their magnitude, for much of the regional climate variability, about 58 percent of Algerian winter rainfall changes, and 68 percent of interannual Mediterranean SST changes. This clearly makes ENSO a powerful remote cause of the hydroclimate in North Africa (Zhang et al., 2021). This Pacific connection quantification is an important development in the predictability of seasonal events and provides a much-needed 3 - 6-month predictive capability for the management of water resources. Despite the robust teleconnections identified, this study has a limitation even though there are strong teleconnections that have been identified. To begin with, relationships may change with a shifting climate as the ENSO signal interference by a background global warming (Fredriksen & Berner, 2023) may change these relationships.

Second, natural variability to the composite results is brought about by inherent uncertainties in reanalysis data (Wills et al., 2022). Lastly, different spatial patterns of ENSO events (e.g., Central Pacific vs. Eastern Pacific El Niño) are not stratified by the analysis, as the different events have different teleconnections, which may modulate the impacts being observed in the Mediterranean. The next generation of research ought to be on experimenting the strength of these linkages in climate model forecasts and stratify studies by ENSO flavors to come up with more sophisticated and robust adaptation strategies (Lee et al., 2022).

## 5. Conclusion

This study provides a comprehensive analysis of the physical processes that con-

trol the interannual variability of winter (DJF) rainfall in northern Algeria between 1993 and 2023 and has robustly linked Mediterranean Sea Surface Temperature (SST) as the primary oceanic controller of this variability. This study defines a consistent narrative of ocean-atmosphere-land interaction, both in global teleconnections and regional precipitation patterns, by combining high-resolution observational data, Empirical Orthogonal Function (EOF) analysis, and advanced composite diagnostics of atmospheric fields. The research began by defining the essential climatological background: the Mediterranean Sea is the main source of moisture for Algeria, and the DJF cycle accounts for more than 70 percent of the annual precipitation in the north, which supports the concentration of population and agriculture. The existence of a steep north-south precipitation gradient, rapidly declining from the coast to the Saharan zone, explains the susceptibility of this narrow productive region to climatic variations. The most significant result of this paper is the discovery that the second mode of Mediterranean SST variability (EOF2) is the most significant cause of interannual rainfall variability. While the first mode (EOF1) described a warming trend across the entire basin, it was EOF2, a zonal dipole pattern with simultaneous warming in the western Mediterranean and cooling in the east, that explained 25.3% of the SST variance and was best correlated with Algerian precipitation. The associated principal component (PC2) was found to be highly interannual without a strong long-term trend, making it a good index for diagnosing year-to-year climatic changes. This relationship was confirmed through a parallel EOF analysis of precipitation, which shows a dipole pattern over Algeria that oscillates in phase with the Mediterranean SST dipole. The atmospheric pathway of PC2 forcing was accurately described in composite analyses using the extreme phases of PC2. During a warm phase, a strong cyclonic anomaly develops in the western Mediterranean, characterized by a sea level pressure deficit of up to  $-1.5$  hPa. This cyclonic circulation drives precipitation increases by performing two essential roles; it enhances strong low-level westerly moisture advection (up to  $2.1$  m s<sup>-1</sup>) from the sea to the Algerian coast, and it strengthens large-scale upward vertical motion ( $-0.12$  Pa s<sup>-1</sup>). This results in a substantial increase in convective activity indicated by strongly negative outgoing longwave radiation (OLR) anomalies as low as  $-12$  W m<sup>-2</sup>, which, in interaction with orographic forcing on the windward slopes of the Tell Atlas, leads to greater-than-normal precipitation. This system is thermodynamically fueled by warm SST conditions via increased evaporation saturating the mid-troposphere with moisture, as observed in relative humidity anomalies exceeding  $+15\%$  -  $20\%$  at 700 hPa. Conversely, during cool SST phases, an anticyclonic regime prevails, shown by a positive SLP anomaly of  $+1.2$  hPa. This pressure system inhibits rainfall through atmospheric subsidence ( $+0.09$  Pa s<sup>-1</sup> omega anomalies), suppresses convection, and reduces moisture advection. The effect is a significant reduction in cloudiness and rainfall, indicated by positive OLR anomalies and mid-tropospheric drying, with relative humidity decreasing by  $-12\%$  to  $-18\%$ , and up to  $-22\%$  in rain-shadow areas such as the Chelif Basin. Finally, this study contextualizes these re-

gional processes within the global climate system. Composite global SST and upper-level velocity potential diagnostics showed that the Mediterranean SST dipole is often a remote response to the El Niño-Southern Oscillation (ENSO). Statistically significant warm phases of EOF2 are associated with El Niño events, in which warm SSTs in the central/eastern tropical Pacific drive upper-level divergence, inducing a stationary Rossby wave train that propagates to the mid-latitudes generating the cyclonic environment over the Mediterranean. This teleconnection explains why ENSO is a strong remote driver, accounting for approximately 58 percent of Algerian winter rainfall variance and 68 percent of interannual Mediterranean SST variability.

The strong correlation between the Mediterranean SST dipole (EOF2) and ENSO is providing a strong instrument of a season forecasting. The lead time of 3 - 6 months of ENSO predictions enables water resources to be managed ahead of time. The co-occurrence of an El Niño event and positive Mediterranean SST dipole can serve as a reliable indicator for a high probability of wet conditions. It would allow the managers to adopt such a strategy as pre-emptive drawdown in northern dams to reduce the risk of floods and maximize storage capacity to expected inflows. Reciprocally, high drought risk would be signaled by a La Niña/cool dipole signal, which will trigger conservation of water, prioritize crops resistant to drought, and plan the irrigation water wisely. With this SST-ENSO framework integrated into the systems of early warning, agricultural and water sectors are in a position to move away with reactive approaches to climate change and embrace proactive action.

In conclusion, this work establishes that the zonal dipole mode (EOF2) of interannual Mediterranean SST variability and its associated atmospheric teleconnections are more important predictors of the winter hydroclimate in Algeria than the warming trend itself. The results represent a paradigm shift in the interpretation of regional climate drivers; they provide a solid physical framework for improving seasonal predictions. With the Mediterranean warming at an accelerating rate, understanding and predicting this SST-rainfall process is not only necessary but also a pressing need for the water security and socioeconomic well-being of Algeria.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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