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Evidence of 2024 Summer as the Warmest During the Last Four Decades in the Aegean, Ionian, and Cretan Seas

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Abstract: The summer of 2024 witnessed record-high sea surface temperatures (SST) across the Aegean, Ionian, and Cretan Seas (AICS), following unprecedented air heatwaves over the sea under a long-term warming trend of 0.46 °C/decade for the mean atmospheric temperature (1982–2024). The respective mean SST trend for the same period is even steeper, increasing by 0.59 °C/decade. With mean summer surface waters surpassing 28 °C, particularly in the Ionian Sea, the southern Cretan, and northern Aegean basins, this summer marked the warmest ocean conditions over the past four decades. Despite a relatively lower number of marine heatwaves (MHWs) compared to previous warm years, the duration and cumulative intensity of these events in 2024 were the highest on record, reaching nearly twice the levels seen in 2018, which was the warmest until now. Intense MHWs were recorded, especially in the northern Aegean, with extensive biological consequences to ecosystems like the Thermaikos Gulf, a recognized MHW hotspot. The strong downward atmospheric heat fluxes in the summer of 2024, following an interannual increasing four-decade trend, contributed to the extreme warming of the water masses together with other met-ocean conditions such as lateral exchanges and vertical processes. The high temperatures were not limited to the surface but extended to depths of 50 m in some regions, indicating a deep and widespread warming of the upper ocean. Mechanisms typically mitigating SST rises, such as the Black Sea water (BSW) inflow and coastal upwelling over the eastern Aegean Sea, were weaker in 2024. Cooler water influx from the BSW decreased, as indicated by satellite-derived chlorophyll-a concentrations, while upwelled waters from depths of 40 to 80 m at certain areas showed elevated temperatures, likely limiting their cooling effects on the surface. Prolonged warming of ocean waters in a semi-enclosed basin such as the Mediterranean and its marginal sea sub-basins can have substantial physical, biological, and socioeconomic impacts on the AICS. This research highlights the urgent need for targeted monitoring and mitigation strategies to address the growing impact of MHWs in the region.

Keywords: marine heatwaves; Mediterranean Sea; ocean warming; SST; climate change

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1. Introduction

The Aegean, Ionian, and Cretan Seas (AICS) are located in the northeastern Mediterranean Sea and control the connectivity between the Black Sea and the broader Mediterranean basin. The AICS are surrounded by an extensive and topographically complex coastline (Greece and Türkiye), controlling the physical processes and productivity of the eastern part of the Mediterranean Sea [1–3]. The spatially averaged sea surface temperature (SST) trend over the entire AICS region is +0.49 °C/decade, with stronger local gradients over the Aegean Sea (for the 1982–2018 period [4], for the 2008–2021 period [5], and for the 1991–2020 period [6]), which is higher than the general Mediterranean trend (+0.40 °C/decade for the 2003–2019 period [7]). This positive trend is aligned with the increasing trend of the atmospheric temperatures over the area, which reached the value of +1.5 °C during the last 30 years, while it exceeds +2 °C mainly in the northwestern part of Greece [6]. The atmospheric warming over this region is much higher (almost double) than the global temperature trend of ~0.6–0.8 °C during the same period [8]. According to the preliminary meteorological data analysed by the National Observatory of Athens's weather service [9] and confirmed by the Copernicus Climate Change Service [10], Greece experienced an extended period of intense heat waves in the summer of 2024, with June and July being the hottest months ever recorded for the country, while August ranked second only to 2021 [11]. Recent meteorological reports [12] also showed that 2024, and especially its summer months, were the warmest recorded in history for Greece.

The Mediterranean Sea is considered to be a hotspot for the formation of marine heatwaves (MHWs) [13] due to its semi-enclosed topography and its location within the transitional space between the temperate and sub-tropical/tropical zones. It has also been characterised by a trend of more frequent, intense, and longer MHWs during the 1982–2021 period [14]. Ibrahim et al. [15] showed that the MHW frequency increased by 1.2 events/decade over the Eastern Mediterranean between 1982 and 2020. The increase is even higher for the summer MHWs over the last four decades [16]. Androulidakis and Krestenitis [5] showed that the spatially averaged number of MHWs over the AICS increased by approximately two events/decade in the 2008–2021 period, while their duration increase was around 21 days/decade. Moreover, there are sub-regions that revealed even higher trends, such as the vulnerable coastal area of Thermaikos Gulf in the Northwestern Aegean, which showed a very strong positive trend of MHW intensity due to the profoundly increasing sea temperature trends (0.52 °C/decade for the 1982–2023 period) [17] that were associated with the increasing atmospheric temperatures in Northwestern Greece [6]. The raised sea temperatures had extensive biochemical implications and ecological impacts on the biotic environment of the AICS. The most important recorded impacts are the decline of seagrass (*Posidonia oceanica*), especially in the Ionian and North Aegean [18]; the coral mortality in the North Aegean (e.g., 60% necrosis in the summer of 2021) [19]; the mussels' mortality, especially in the summer of 2021 [20]; the invasion of thermophilous alien species in the South Aegean and Cretan Sea [21]; and the migration of pelagic fish (e.g., sardinella movement to the north) [22]. The summer of 2021 was characterised by the warmest ever recorded SST until then over the AICS region [5], and it imposed significant impacts on several ecological aspects. However, the most recent summer of 2024 might have exceeded the 2021 levels (i.e., the warmest ever recorded), potentially inducing even more hazardous effects on the ecosystems of the AICS region.

Besides the prevailing atmospheric conditions (air temperature, heat fluxes, barometric pressure, wind-driven circulation, air humidity, cloudiness, precipitation patterns, etc.), the interannual, seasonal, and spatial variability of the sea temperature is determined by specific ocean processes. The Aegean Sea undergoes intense water exchanges with the Black Sea (Black Sea waters: BSW) that occur through the Dardanelles Strait [23]. The BSW plume is lighter (very than the underlying Aegean layers and thus remains close to the surface [24], affecting the physical variability of the Aegean Sea [25]. A recent study [26] showed a drastic reduction of BSW presence in the surface layer of the Aegean Sea, affecting several physical processes such as dense water formation, which became more frequent during the recent decades, especially in the northern part of the basin [25,27–29]. The Eastern Aegean is also influenced by the wind-driven Ekman transport and the associated upwelling processes [30] that bring colder waters to the surface and have a cooling effect on mean temperature values, especially during the summer months [31–33], when strong northerly winds usually prevail (Etesians winds or Meltemia) [34] across the Aegean Sea from north to south. The physical characteristics of the Cretan Sea are highly controlled by its interactions with the Levantine Sea in the east and the South Ionian Sea in the west [35]. Finally, the North Ionian Sea is connected with the Adriatic Sea, while the West and South Ionian are influenced by the circulation patterns of the Central Mediterranean [36].

The current study seeks to extend the results of Androulidakis and Krestenitis [5] over the AICS, who focused only on the surface variability between 2008–2021, by using a longer study period (1982–2024). Herein, our focus is on the extreme warming conditions of the summer of 2024 and on the prevailing environmental conditions over specific sub-regions of interest. The initial hypothesis of this study is that the prevailing atmospheric conditions over the AICS during the summer (June–August) of 2024, combined with several other ocean factors (e.g., upwelling processes and lateral fluxes), have increased the sea temperature to the highest levels recorded during the last four decades of available remote sensing observations. The air-sea heat fluxes are two-way processes affecting both the atmosphere and the ocean. The main factor of ocean warming is related to the prevailing atmospheric conditions (e.g., air temperature, humidity, winds, radiations, heat fluxes, and winds). Moreover, it is influenced by the recorded respective increasing trends in ocean temperatures at both global and regional scales due to the looming climatic changes in both atmospheric and seawater conditions. Our main goal is not only to provide evidence that the summer of 2024 was the warmest in recent records (1982–2024) regarding the sea temperature but also to identify the characteristics and the environmental conditions of the exceptional sea temperature conditions over the entire AICS. The variability of MHWs that occurred under these conditions over the AICS is also examined, while their spatial and temporal distribution compared to previous decades is further identified.

Satellite observations are used to detect the SST distribution and the chlorophyll-a (CHL) variability to identify the BSW evolution over the Aegean Sea (Section 2.1). The vertical temperature distribution over the upper ocean is investigated with the use of available measurements collected by ARGO floats (Section 2.2) that travelled over the AICS and were active during the summer of 2024. The meteorological conditions are assessed based on the ERA5 dataset (Section 2.3), focusing on the variability of the winds during the summer months. The surface temperature and the MHW variability are presented in Section 3.1, while the upper-ocean conditions are discussed in Section 3.2. The prevailing atmospheric conditions and the upper-ocean cooling mechanisms over the Aegean Sea are presented in Sections 3.3 and 3.4, respectively. Appendix A presents the predominant geostrophic circulation over the broader Mediterranean Sea during the summer of 2024. The study's findings and implications are discussed in Section 4, and Section 5 presents the main concluding remarks.

2. Methods and Data

2.1. Satellite Observations

Satellite-derived SSTs were obtained through the Copernicus Marine Service (CMS) [37]. The SST daily gap-free dataset is a Level 4 reprocessed diurnal product [38,39] and, for the purposes of this study, covers the AICS (19° E–28.5° E, 34° N–41° N) with a spatial resolution of 0.05° from January 1982 to August 2024 (43 years). The SST fields were used to compute the interannual evolution and spatial variability of the SST and to detect MHWs following the methodology introduced by Hobday et al. [13]. MHWs are defined on the basis of abrupt SST increases above a "climatological" value (the baseline temperature) for a certain time period, suggesting that a period over 30 years is required to estimate the 90th percentile baseline temperature ($SST_{Threshold}$) [13]. According to this definition, a MHW is defined as a "discrete and prolonged anomalously warm ocean-based event". The term "discrete" implies that the MHW is an identifiable event with clear start and end dates, and the term "prolonged" means that it has a duration of at least five days. "Anomalously warm" means that the water temperature is warm compared to the $SST_{Threshold}$. The baseline temperature used in the present study is defined by the seasonal (monthly) varying 90th percentile, derived from the 1982–2024 SST data in the resolution (0.05°) of the AICS domain. The cumulative intensity (CI) of a MHW is determined by summing all daily intensities, which are the number of degrees above the $SST_{Threshold}$ for those days (Equation (1)):

$$CI = \sum_{i=1}^{N} Daily\ Intensity \quad (1)$$

where "Daily Intensity" is the difference between the observed SST_{Daily} and the $SST_{Threshold}$ and N is the MHW duration in days. The CHL data, used in the study to estimate the BSW spreading over the Aegean Sea [26], were derived from a high resolution (1 km) gap-free daily Level 4 reprocessed product of CMS [37,40–42], spanning from January 1997 until August 2024.

2.2. Argo Floats

ARGO floats deployed in the AICS provide information about the variability of the interior of the water column in the region [43]. Eight ARGO floats that were active during the summer of 2024 across the AICS regions were used to estimate the vertical temperature distribution over all AICS sub-regions (Figure 1). Three ARGOs with World Meteorological Organization Identities (WMO ID) 6903822, 6903803, 6903296 drifted over the Ionian Sea, three crossed the Cretan Sea (WMO ID: 6903803, 6903296, 6903297), and five collected measurements over the broader Aegean Sea (WMO ID: 6903297, 7901017, 6903298, 1902582, 3902474). All the active floats during the summer of 2024 (solid lines in Figure 1) were deployed in the sea between September 2021 and April 2024, and all the collected profiles along their trajectories were analysed in this study. Four additional profiles from two more floats (WMO ID: 6901890 and 6903298) were collected over the central Aegean Sea in the summers of 2015 and 2023. All ARGO data were downloaded via the Euro-Argo fleet monitoring tool, which is maintained by the European Research Infrastructure Consortium (ERIC) [44]. Herein, the upper 200 m of each water column profile is shown to identify potential differences between the summer of 2024 and previous years along the upper-ocean layers.

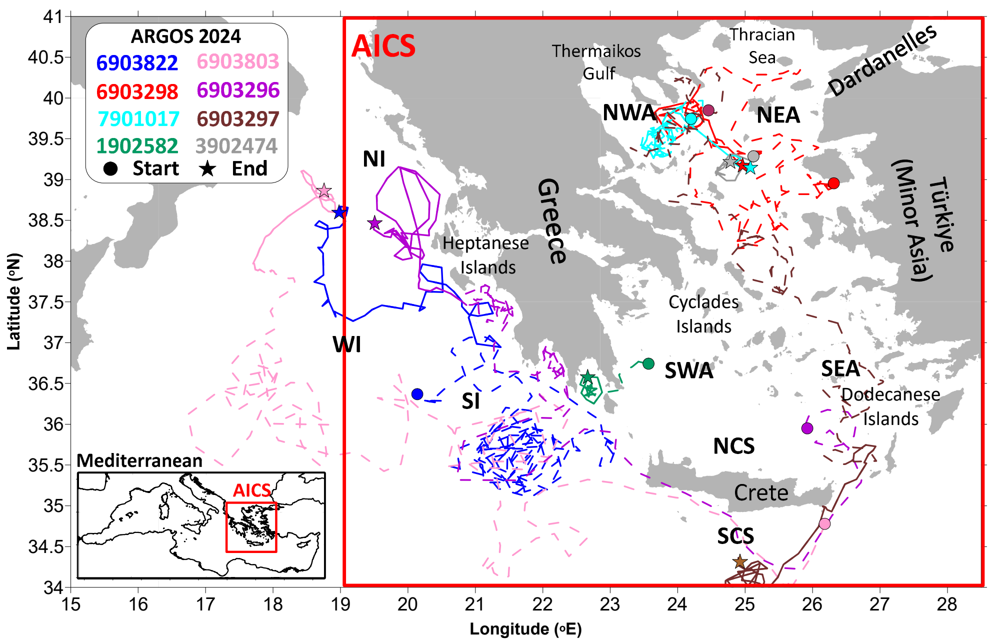

Figure 1. Domain of the Aegean, Ionian, and Cretan Seas (AICS; marked with a red box in the Mediterranean insert map), indicating the sub-domains and the main topographic features referred to in the study. The trajectories of eight available ARGO floats between 2021 and 2024 that were still active in the summer of 2024 (solid lines) are also shown (the dashed lines represent the trajectory parts before 2024). The start and end of each trajectory are marked with a circle and star, respectively. The sub-regions of the AICS are marked: North Ionian (NI), West Ionian (WI), South Ionian (SI), North Cretan Sea (NCS), South Cretan Sea (SCS), Northeastern Aegean (NEA), Northwestern Aegean (NWA), Southeastern Aegean (SEA), and Southwestern Aegean (SWA).

2.3. Meteorological (Atmospheric) Data

The meteorological conditions for the study domain and period (1982–2024) were derived from the ERA5 hourly data on single levels distributed by the CCCS [10]. The ERA5 dataset is a fifth-generation ECMWF reanalysis that combines model data with observations (data assimilation) and provides hourly estimates for a large number of atmospheric quantities [45]. Herein, we used the 6-hourly meridional and zonal components of the wind at a height of 10 m above the sea surface to compute the variability of the wind speed and direction over the Aegean Sea and examine any potential changes during the summer of 2024. In addition, we collected the air temperature at 2 m above the surface, which is produced by the interpolation between the lowest model level and the Earth's surface, taking into account the atmospheric conditions. The respective surface net shortwave solar radiation (Q_S), the surface net longwave backscatter radiation (Q_b), the surface sensible heat flux (Q_h), and the surface latent heat flux (Q_e) were also obtained from ERA5 to estimate the interannual variability of the surface net heat flux (Q_T; Equation (2)) over the 1982–2024 period. The spatial resolution of all atmospheric fields is 0.25°.

$$Q_T = Q_S + Q_b + Q_e + Q_h \quad (2)$$

3. Results

3.1. Sea Surface Conditions and Marine Heatwaves

The interannual variability of the mean summer SST, averaged over the AICS domain (Figure 1), reveals a significant positive trend during the 43-year period (1982–2024), with an increasing level from around 23 °C in 1982 to over 26 °C in 2024 (Figure 2a). The Sen's Slope [46] of the trend that provides the annual change of the variable under investigation is 0.59 °C/decade (statistically significant: $p_{value} < 0.0001$) [47,48]. The high autocorrelation of 1-year lag (0.70; Figure 2a) indicates strong short-term persistence in SSTs (correlation between values that are one typical time period apart), where factors affecting it (such as atmospheric forcing, solar radiation effects, or ocean processes) cause consecutive years to have similar temperatures. The autocorrelation then gradually declines by lag 10 (correlation between values that are 10 years apart). It is weak but still positive (0.15), indicating that there may be a longer-term climate signal superimposed that extends beyond individual years but weakens over time. This pattern indicates that the accumulation of heat in the ocean surface layers through the years might have served as an additional factor for the increasing sea temperature trends. The highest mean summer SST was detected in the recent summer of 2024, when very high temperatures were measured in the Northwestern Aegean, the Ionian, the South Cretan, and the Southeastern Aegean Seas (Figure 2c).

The 2024 summer SST levels were always higher than the respective climatological levels for the entire region, ranging from 1 °C higher in the central Aegean to more than 3 °C in the rest of the AICS region (Figure 2d), especially in mid-July (Figure 2b). It is noteworthy that the spatially averaged daily SSTs are higher than the climatological values during the entire year (January to August). The SST anomaly of 2024 shows a strong variability during the summer, following a notable peak and drop in April and May, respectively (Figure 2b). The net heat flux (Equation (2)) in the surface shows a similar variability, especially after April (negative values before March are not shown for clarity reasons). Although other met-ocean physical processes (see Section 3.4 and Appendix A) may also contribute to the heat budget and the SST variability, the variations of the SST usually coincide with respective heat gains (e.g., early and mid-April, early June, early to mid-July) and losses (e.g., late April, early to mid-May, August) from the sea surface. The general heat flux variability and trends are analyzed in Section 3.3.

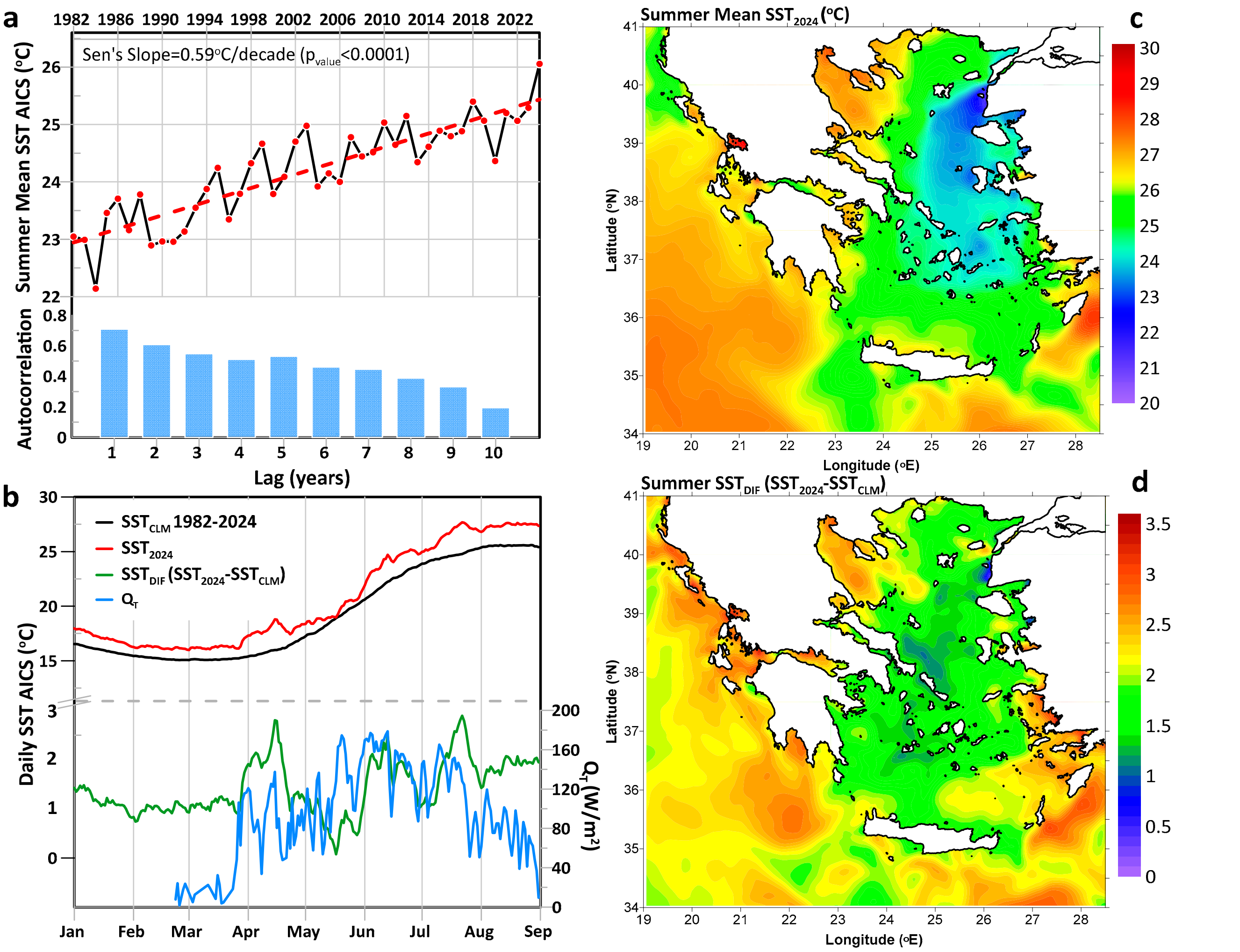

Figure 2. (**a**) Interannual evolution of the summer sea surface temperature (SST) from 1982 to 2024, spatially-averaged over the Aegean, Ionian, and Cretan Seas (AICS), and the respective autocorrelation coefficients for lags between 1 to 10 years. (**b**) Daily SST (SST_{2024}; red line), mean climatology (SST_{CLM}; black line), the difference between the SST and climatology ($SST_{DIF} = SST_{2024} - SST_{CLM}$; green line), and net heat flux (Q_T; blue line) with excluded land and negative values before March for presentation clarity in 2024. Maps of (**c**) mean SST and (**d**) SST_{DIF} for the summer of 2024. The linear trend and the respective Sen's Slope (and p_{value}) are shown in (**a**).

The lowest sea temperature values were detected in the East Aegean Sea (Figure 2c), where BSW waters spread, and extensive upwelling of deeper and colder waters usually takes place [32,33]. However, even in these areas, the summer levels of 2024 are considerably higher than the climatological levels (~2 °C; Figure 2d). Possible changes in the mechanisms that contribute to the marine temperatures' variability of the Aegean are discussed in Section 3.4. The Ionian Sea also revealed very high SST anomalies (Figure 2d). Apart from the direct heat exchanges with the atmosphere (Section 3.3), the near-surface temperature is also determined by horizontal transport processes and exchanges with the broader Central Mediterranean, the Adriatic Sea, and the SW Aegean [49]. To a lesser extent, the near-surface temperature is influenced by transport and mixing processes in the vertical, as it is well known that, contrary to the East Aegean Sea, coastal upwelling rarely occurs along the west coasts of Greece (Ionian Sea) [30]. More information about the exchanges with marginal areas is presented in Appendix A. These results confirm that the extremely warm conditions of 2024 with respect to the atmospheric conditions were also evident in the SST patterns during the entire year and especially during its hot season, characterising it as the warmest summer on recent (43-year) records with respect to the ocean temperatures.

The interannual evolution of MHWs, computed in each of the domain's nodes (0.05° resolution) and averaged over the AICS, shows an increasing trend from 1982 to 2023 by approximately 0.8 events/decade (Figure 3), with higher numbers (>4 events) after 2010, in agreement with Androulidakis and Krestenitis [5], who showed that the Sen's Slope was even higher between 2008 to 2021 (~2 events/decade). The interannual trend, based on the first 8 months of each year (January–August), including 2024, is also strong and positive (red line; 0.5 events/decade). The number of MHWs during the first 8 months of 2024 was similar to its respective periods of several recent years, and it was even smaller when compared to 2010. The total duration (>160 days), though, and especially the cumulative intensity (CI > 300 °C × days) in 2024, was the highest of the entire study period, although the year is not over yet at the time of reporting (September 2024), and more MHWs can potentially be formed during the remaining (autumn/winter) months. The annual MHW total duration is characterised by a statistically significant ($p_{\text{value}} < 0.0001$) trend of 14 days/decade (1982–2023) and 8 days/decade (1982–2024), excluding the period after the summer. The 2024 duration was almost double, higher than the highest-until-now duration in 2018 (80 days). The longest (>200 days) and most intense (>400 °C × days) MHWs of 2024 occurred in the North Aegean (Figure 3). The highest intensities were computed for the northwestern region, where Thermaikos Gulf is located, but strong MHWs also formed over the Thracian Sea (Northeastern Aegean), where colder BSW usually spread. The southern parts of the domain, particularly the South Ionian, the Cretan Sea, and the Southeastern Aegean (Dodecanese islands), also revealed strong MHWs related to exchanges with the Levantine Sea (see Appendix A), matching the highest mean summer SST distribution (Figure 2c).

3.2. Upper-Ocean Conditions

The vertical distributions of the upper-ocean (0–200 m) temperature from the eight active ARGO floats over the AICS domain are presented in Figure 4. The floats have covered almost all AICS areas during their trajectories over the last 3 years and have collected measurements at most of the sub-domains in the summer of 2024: 6903822 in the South Ionian, 6903803 and 6903296 in the North Ionian, 6903298 in the Northwestern Aegean, 6903297 in the Cretan Sea, 7901017 in the Northeastern Aegean, 1902582 in the Southwestern Aegean, and 3902474 in the boundary between the Northeastern and Northwestern Aegean (Figure 1). The measurements show very high temperature levels near the surface in the summer of 2024 compared to previous summers, in agreement with the satellite observations for the same period (Figure 2). Values over 28 °C were also found in depths down to 25 m (e.g., South and North Ionian, Southwestern Aegean, and Cretan Sea). Such high temperatures below the surface were very restricted during the summers of 2022 and 2023. Another noticeable difference is related to the time span of such events of high temperatures, that were longer than the previous years; the warm masses in these upper layers were apparent for more than 1 month in the summer of 2024 in the Ionian Sea (6903822 and 6903803) and the South Aegean (1902582). Colder (<15 °C) deeper waters (>50 m) were detected in the Northwestern Aegean all along 2022; they were also apparent below the seasonal thermocline during the summer-autumn months of that year. Such low temperatures were totally absent in 2023 and especially in 2024 in the upper 200 m. North Ionian was the only region that revealed relatively low temperatures (<17 °C) below 75 m during the summer of 2024. The entire upper water column at the North Aegean in 2024 showed temperatures above 15 °C. It is indicated that the potentially upwelled waters in the Aegean Sea, which originate from shallow depths in this region (<80 m) [32,33], were warmer in the summer of 2024 in comparison to other years, bringing water masses with higher temperatures than usual to the surface under northerly winds in the summer (see Section 3.4).

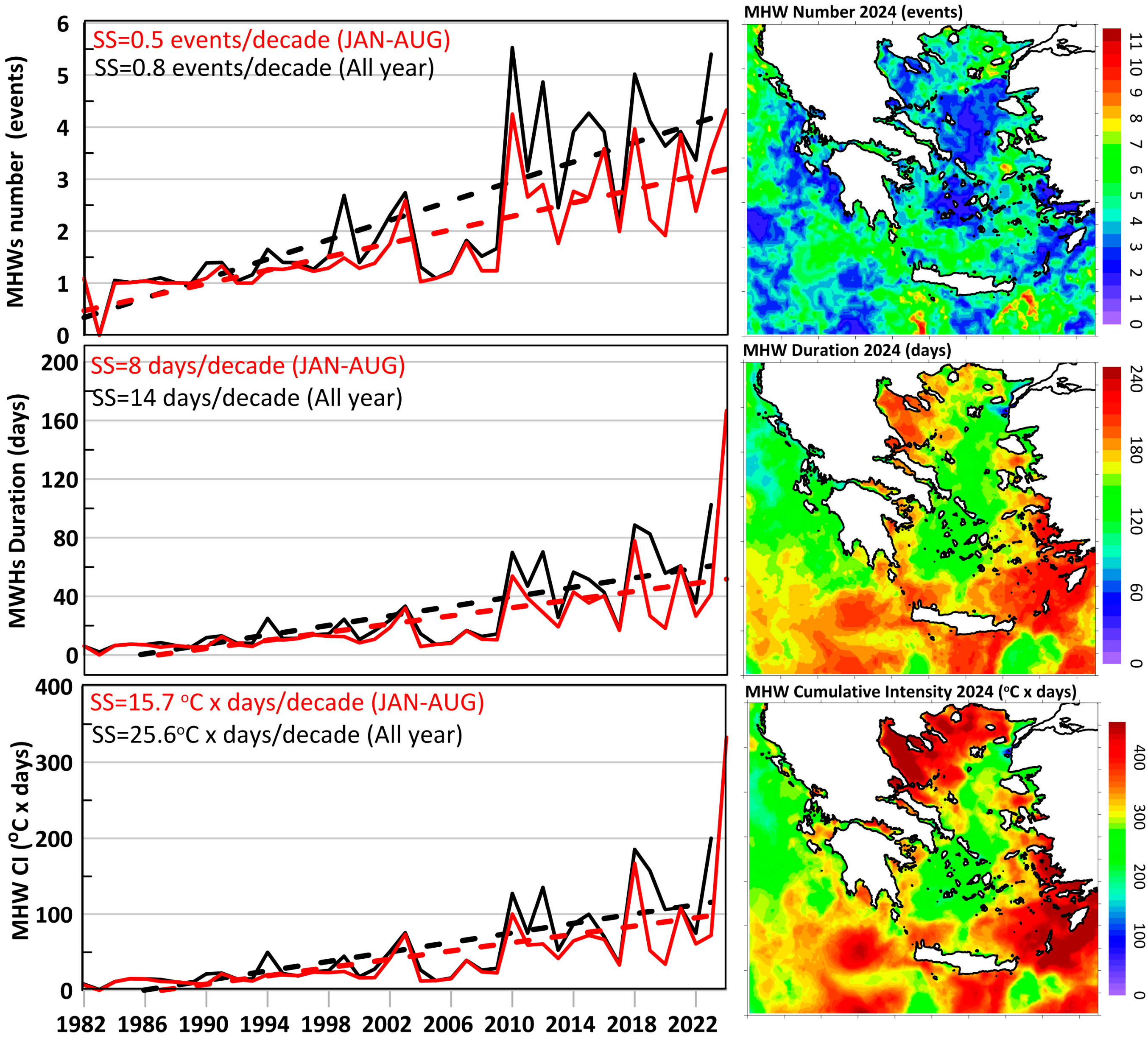

Figure 3. Interannual evolution of spatially averaged number, total duration (days), and cumulative intensity (°C × days) of marine heatwaves (MHWs) from 1982 to 2024 using all months of the year (January–December; black line) and only the first 8 months (January–August; red line). The linear trends (dashed lines) and the Sen's Slope (SS) for each case are presented (**left**). The respective maps for 2024 are shown (**right**). The 2024 computations cover only the period from January to August.

3.3. Atmospheric Conditions

The analysis of the ERA5 dataset (see Section 2.3 for details) showed a very strong increasing trend of the air temperature above the sea (land excluded) during the last 4 decades (0.46 °C/decade; Figure 5a). In agreement with recent reports [12], the ERA5 data showed a strong temperature anomaly for 2024 with respect to the summer climatology over the entire AICS domain, exceeding 2 °C in certain areas of the Ionian Sea, the North Aegean, and the Cretan Sea (Figure 5b). The summer months of 2024 exhibited the highest air temperature of the entire period, exceeding the level of 26 °C, averaged over the AICS region (Figure 5a). The second warmest summer occurred in 2012, and it was around 0.8 °C colder than in 2024. The Pearson correlation coefficient between the mean annual summer air (Figure 5a) and the SST (Figure 2a) is very high, equal to 0.93 and statistically significant (Mann–Kendall correlation test 99%; $p_{value} < 0.01$), confirming a very good agreement between the two time series. The interannual trend of the summer net heat flux (Q_T; Figure 5c) is characterized by a very weak slope, which is not statistically significant ($p_{value} > 0.01$). However, a stronger increase was observed during the recent decade, and especially after 2018, with relatively high levels in the summer of 2024 (114 W/m^2). It is the third highest during the 43-year period, indicating a strong downward transfer of heat to the sea, affecting almost the entire AICS domain (positive differences larger than 5 W/m^2; Figure 5d). The highest anomalies (>25 W/m^2) in the summer of 2024 with respect to the climatology were observed in the Aegean Sea, the West Cretan Sea, and parts of the S. Ionian.

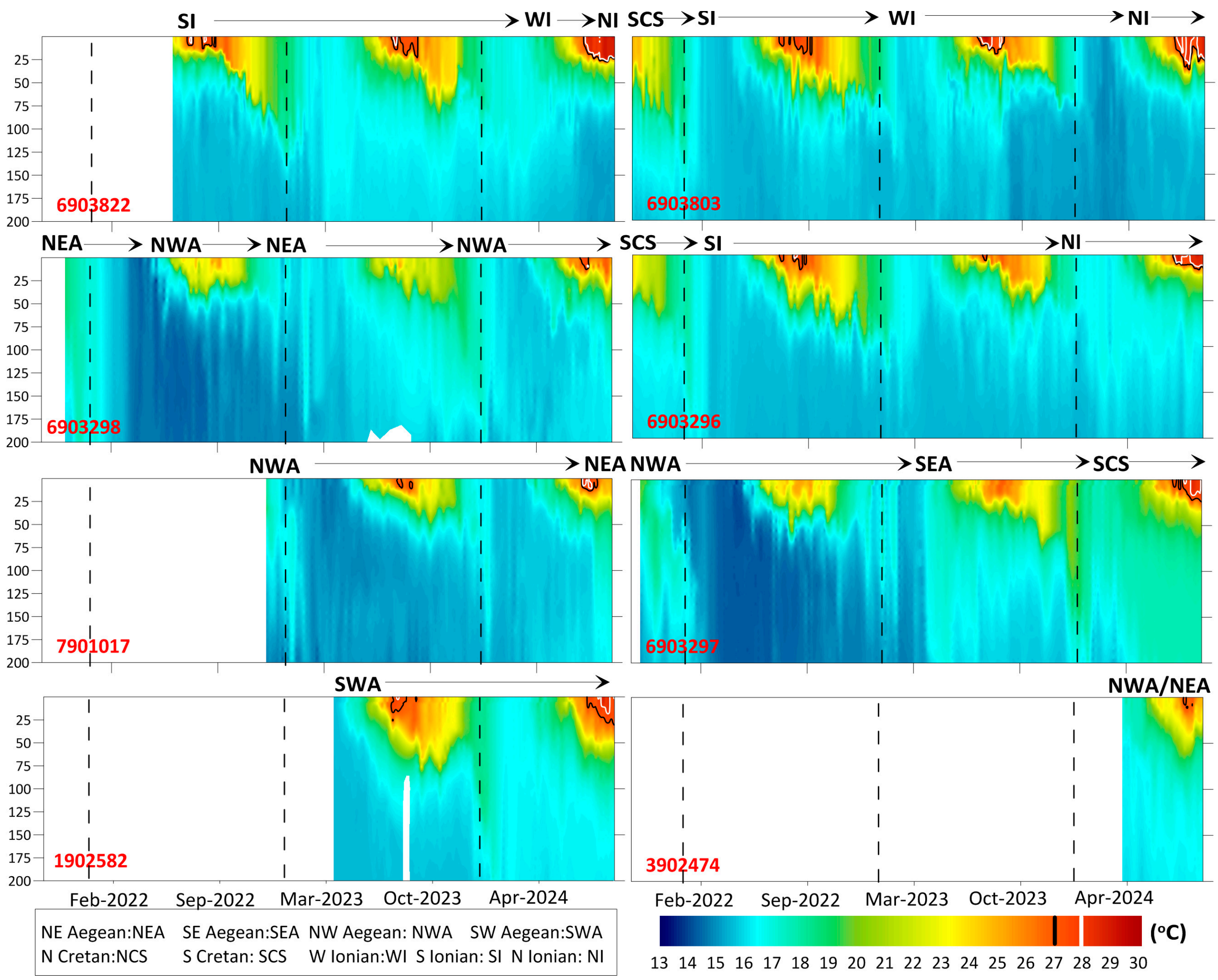

Figure 4. Hovmöller diagrams of the vertical distribution of temperature over the upper 200 m as derived from the trajectories of eight ARGO floats (Figure 1) deployed and propagated across the AICS domain from 2021 until 2024. The sub-domains (marked in Figure 1) covered by the ARGO floats are also marked. The black and white contour lines indicate the 27 °C and 28 °C isotherm, respectively. The vertical dashed lines indicate the 1st of January of each year.

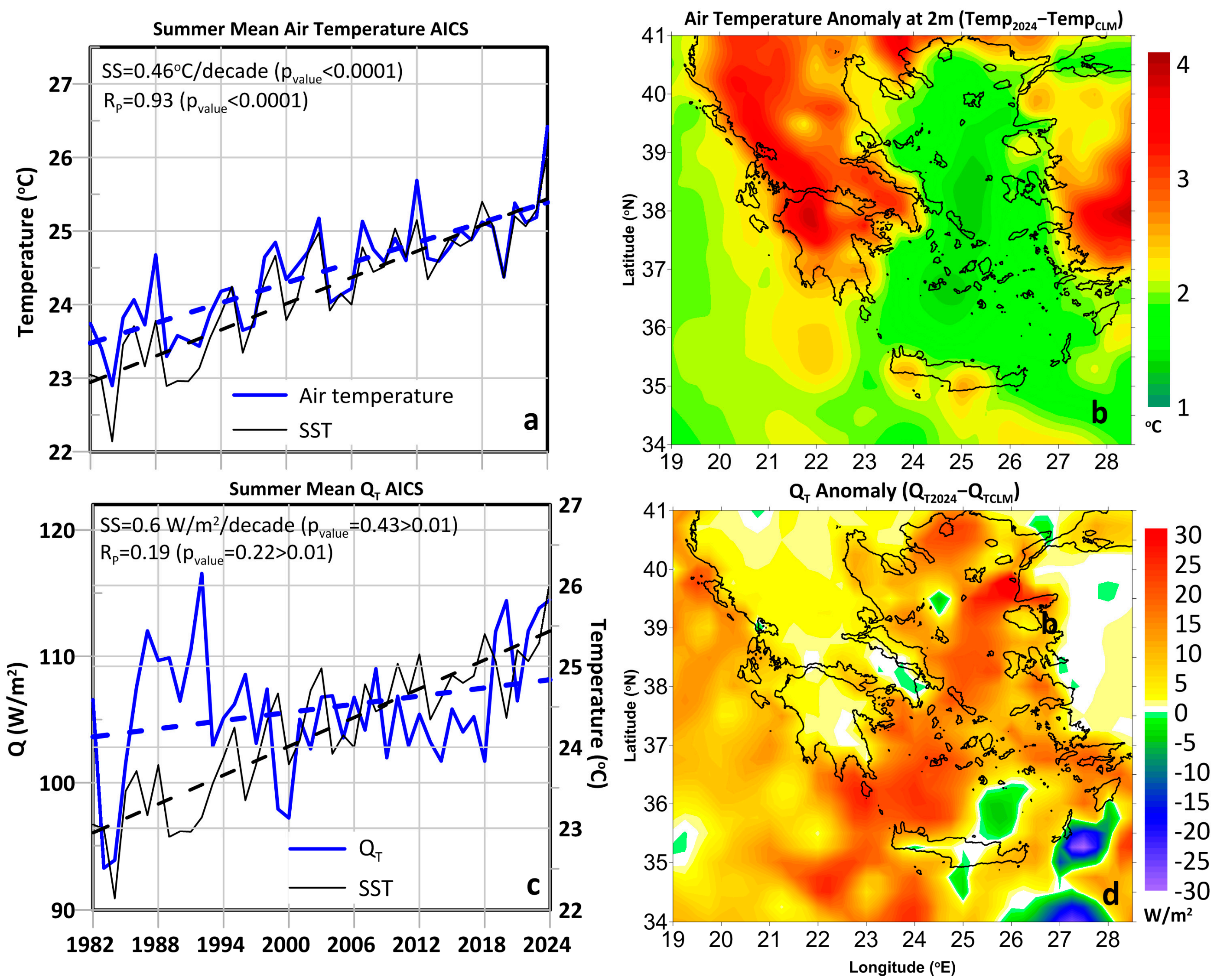

Figure 5. (**a**) Interannual evolution of the summer air temperature (2 m; ERA 5 dataset) from 1982 to 2024, spatially averaged over the Aegean, Ionian, and Cretan Seas (AICS; land excluded). (**b**) Map of the air temperature anomaly between the summer of 2024 ($Temp_{2024}$) and the climatological summer mean ($Temp_{CLM}$), computed for the period of 1982–2023. The time series, trends, and map for the net heat flux (Q_T; W/m^2) are presented in (**c**) and (**d**), respectively (positive values represent the downward radiations). The interannual trend of SST (Figure 2a) is overlaid. The correlation coefficient between radiation and SST (R_P), the linear trend (dashed lines), the Sen's Slope (SS), and the respective p_{value} for each case are shown.

Although the general correlation between the net heat flux and the SST is low (R_P = 0.19), the diversity of the different radiation components (Equation (2)) shows stronger correspondences with the sea temperature variability (Figure 6). The main component of the heat budget is the shortwave net radiation (Q_s; Figure 6a), which is the primary driver of the heat gain of the upper ocean layers during daylight hours. It penetrates the water, where it is absorbed and converted into heat; the correlation coefficient between Q_s and SST is the highest among all components (R_P = 0.49) and is statistically significant (p_{value} < 0.01). The summer shortwave radiation increased through the years (1.5 W/m^2/decade) and showed a peak (285 W/m^2) in the summer of 2024. The highest Q_s anomalies of 2024 (stronger heat gain) were detected in the Northwestern Aegean and in the Ionian Sea (large positive differences with respect to the climatology; Supplementary Material).

The summer longwave net radiation is also well correlated with the SST (R_P = 0.48) and becomes less negative through the years (1.1 W/m^2/decade; Figure 6b), indicating the reduction of heat loss from the ocean to the atmosphere. The longwave radiation in 2024 revealed one of the less negative values (−81 W/m^2) during the last 4 decades, associated with weaker sea cooling that mainly takes place during nighttime. Although the latent heat flux (Q_e) is characterized by an overall negative trend (−1.5 W/m^2; Figure 6c), the last decade (after 2013) shows an increasing tendency. In the Ionian Sea, the heat losses from the sea through the latent radiation were the smallest among all areas (Supplementary Material). This recent increase (lesser negative values) is more profound in the sensible heat flux (Figure 6d). This reduction of heat loss during this period, related to the sensible radiation, is associated with the observed milder temperature gradients between the sea and the air above it after 2013 (Figure 5a). Besides the high air temperatures and the heat fluxes with the atmosphere, other met-ocean conditions (e.g., wind state, lateral ocean fluxes such as the BSW, and the interactions with the broader Mediterranean) may also play a role in the occurrence of abnormally hot ocean waters.

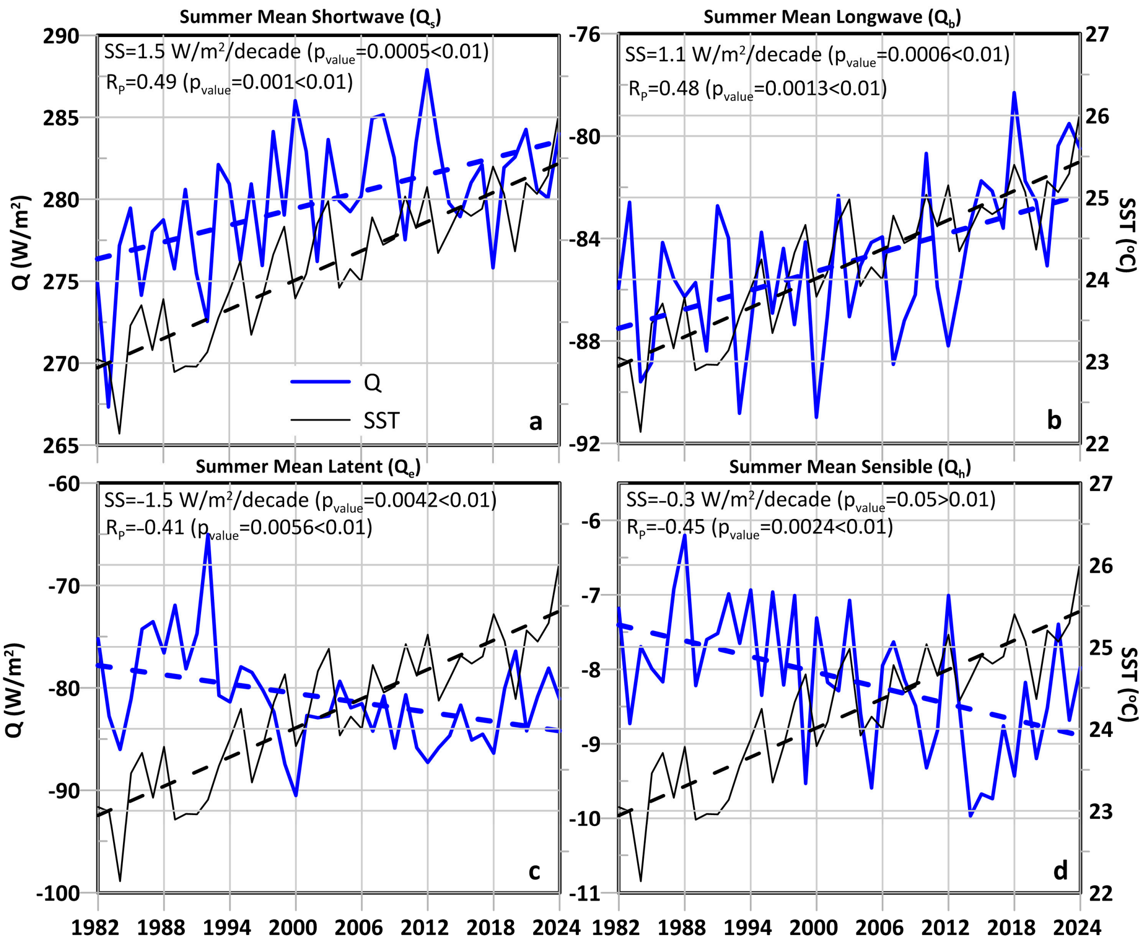

Figure 6. Same as Figure 6c for (**a**) net shortwave radiation (Q_s), (**b**) net longwave radiation (Q_b), (**c**) latent (Q_e), and (**d**) sensible (Q_h) surface heat fluxes.

3.4. Upper-Ocean Cooling Mechanisms in the Aegean Sea

Historically, the lowest summer SSTs and the weakest formation of MHWs occur in the East Aegean [5,50]. This is the main area where BSW spread (Northeastern Aegean), characterised by a colder SST signal during the summer months, and coastal upwelling (along Minor Asia coasts and East Aegean islands) takes place under the Etesians northerly winds, especially in July and August. These relatively colder surface waters were also detected in the mean SST fields during the summer of 2024 (Figure 2c). However, their surface spreading signal was more restricted in comparison to previous years (Figure 7), and thus, the SST difference between 2024 and the climatological levels is positive and relatively high everywhere (>1 °C; Figure 2d). Surface water masses with temperatures lower than 24 °C during the summer of 2024 spread south of the Dardanelles exits but were restricted north of parallel 38° N, limited compared to the period of 2021–2023 (Figure 7); in all of those years, the colder waters, related to both BSW and coastal upwelling, covered extensively larger parts of the Aegean Sea. Moreover, the respective MHW durations and intensities in 2024 were high along the Minor Asia coasts (south of parallel 38° N; Figure 3).

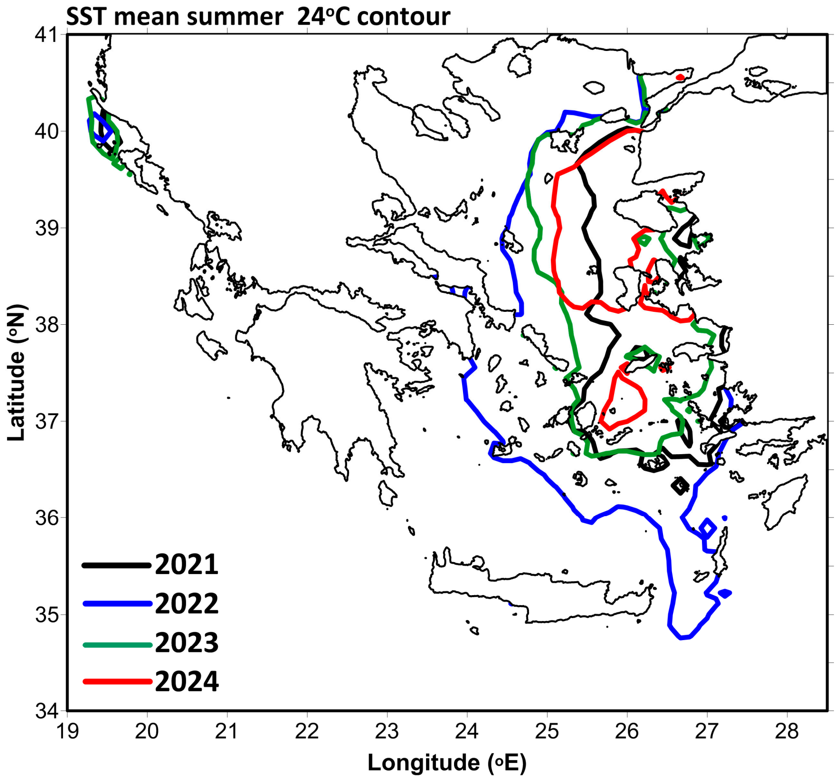

Figure 7. Evolution of the 24 °C isotherm derived from the surface summer means of 2021, 2022, 2023, and 2024.

The northerly winds over the Aegean in the summer of 2024 were more frequent and stronger (Figure 8a) than their climatology levels (Figure 8b), enhancing the coastal upwelling processes along the East Aegean basin. The wind state also showed a stronger southward component compared to the climatological levels (negative values in Figure 8c), indicating the dominance of strong northerly winds over the Aegean Sea (Etesians). Thus, a stronger signal (lower temperatures) would be expected for the summer of 2024, since the northerly winds, responsible for the coastal upwelling, were stronger than the ones in previous years, which is not evident from the spread of low-temperature surface waters (Figure 7). A possible reason lies in the fact that the temperature levels of the subsurface layers (40–80 m), which are the main origin of the upwelling masses, have been generally higher in 2024 compared to previous years (Figure 4). Thus, the upwelled waters that reached the surface of the East Aegean were warmer in 2024, weakening the mechanism that would hold back the strong SST increases and prevent the formation of MHWs.

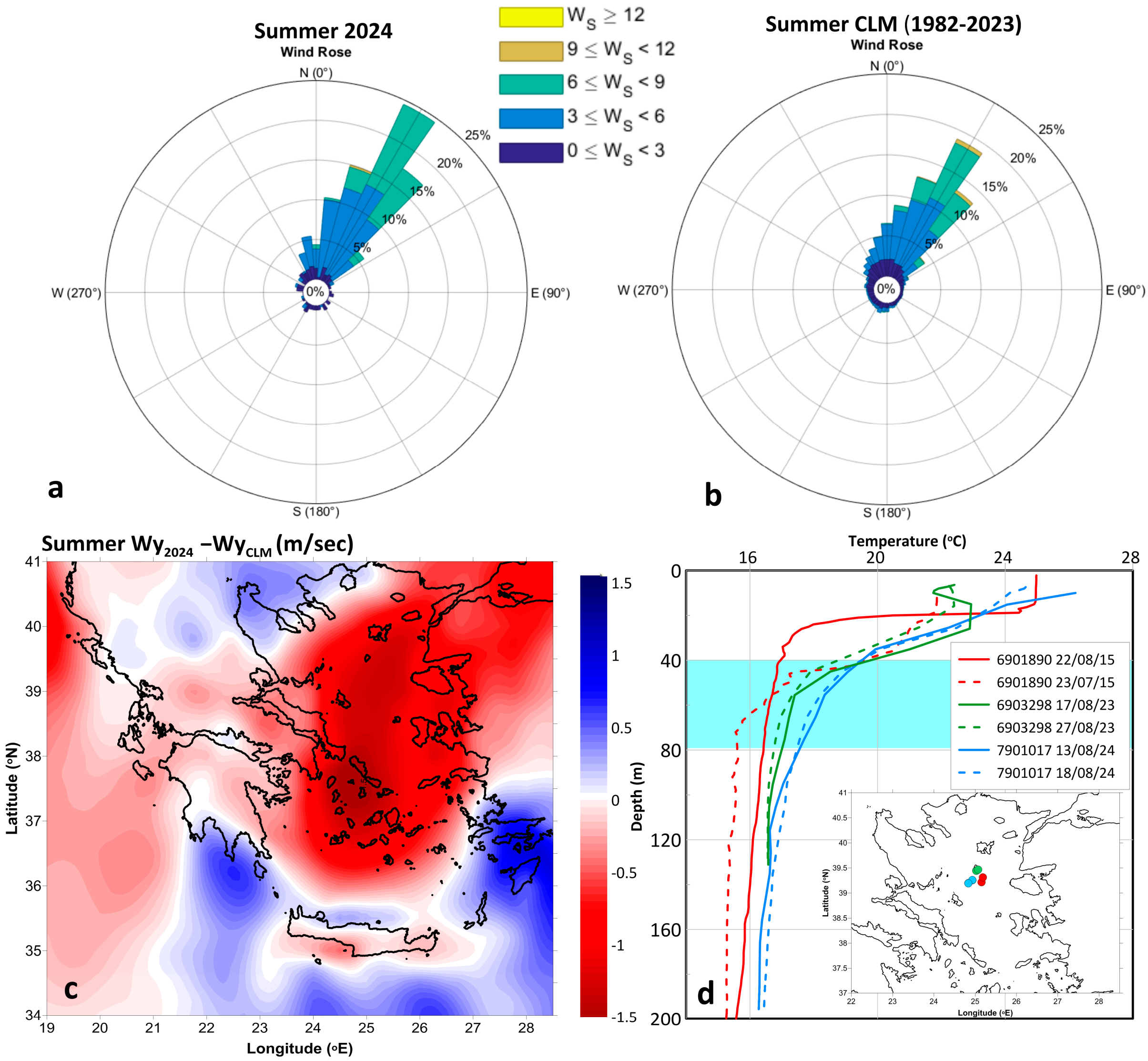

Figure 8. Wind rose diagrams for (**a**) the 2024 winds and (**b**) climatological winds, spatially averaged over the Aegean Sea (dashed box in panel (**c**), land excluded). (**c**) Map of the summer anomaly of the meridional wind (Wy; negative values for northerlies and positive for southerlies) component between the year 2024 and the climatology (CLM; 1982–2023) over the AICS domain. (**d**) Six ARGO temperature profiles from the summers of 2015, 2023, and 2024. The locations of the profiles are marked with colored dots in the insert map. The blue-shaded area marks the depth range of the upwelling origin over the Aegean Sea [32,33].

The warmer state of the subsurface layers in 2024 is also indicated by the comparison between an ARGO float that collected profile measurements over the East Aegean Sea in August of 2024 (7901017) and the respective profiles from two currently not-active ARGOs (6901890 and 6903298) over the same area during the upwelling season of 2015 and 2023, respectively (Figure 8d). The 2024 values inside the upwelling depth (40–80 m) were considerably higher among the three summers (two profiles for each ARGO float); the temperature difference ranged between 1 to 3 °C, indicating the warmer waters over these depths in 2024. The water column in 2024 was warmer over the entire 200 m layer in comparison to all the older profiles. The upwelling of these warmer waters, together with the extreme atmospheric conditions, contributed to the relative increase of the cumulative intensity of the surface MHWs (Figure 3) over this usually colder region of the Aegean (Figure 7).

In addition, the spreading of BSW (generally of higher CHL concentrations compared to the Mediterranean water masses) was limited in 2024 following the general reducing interannual trend of BSW outflow [26]. The lowest CHL concentrations, averaged over the Northeastern Aegean from January to August, were measured in 2024 (Figure 9a) over an area that is usually covered by water of Black Sea origin as derived by the respective climatological CHL concentrations (Figure 9c). The difference between the CHL levels in 2024 and the climatological levels is negative everywhere, indicating the weak spreading of the colder BSW (Figure 9d). The minimum CHL concentrations were apparent for the entire period until August of 2024, with a deep low in mid-spring and a continuous negative difference with the climatological values until the end of August (Figure 9b). Intense MHWs occurred over the northern parts of this region (Thracian Sea; Figure 3). The minimal spreading of the BSW during 2024 combined with the warmer upwelled waters during summer are favourable pre-conditions for the higher SST levels and the MHWs detected over the Aegean Sea. Although the main driving factors of MHWs are related to extreme atmospheric conditions (e.g., peaks of downward surface heat fluxes), the notable changes in these two cooling down mechanisms of the Aegean, as observed in the summer of 2024 compared to previous summers, are crucial for the future variability of physical processes in the area, and require further investigation and targeted studies.

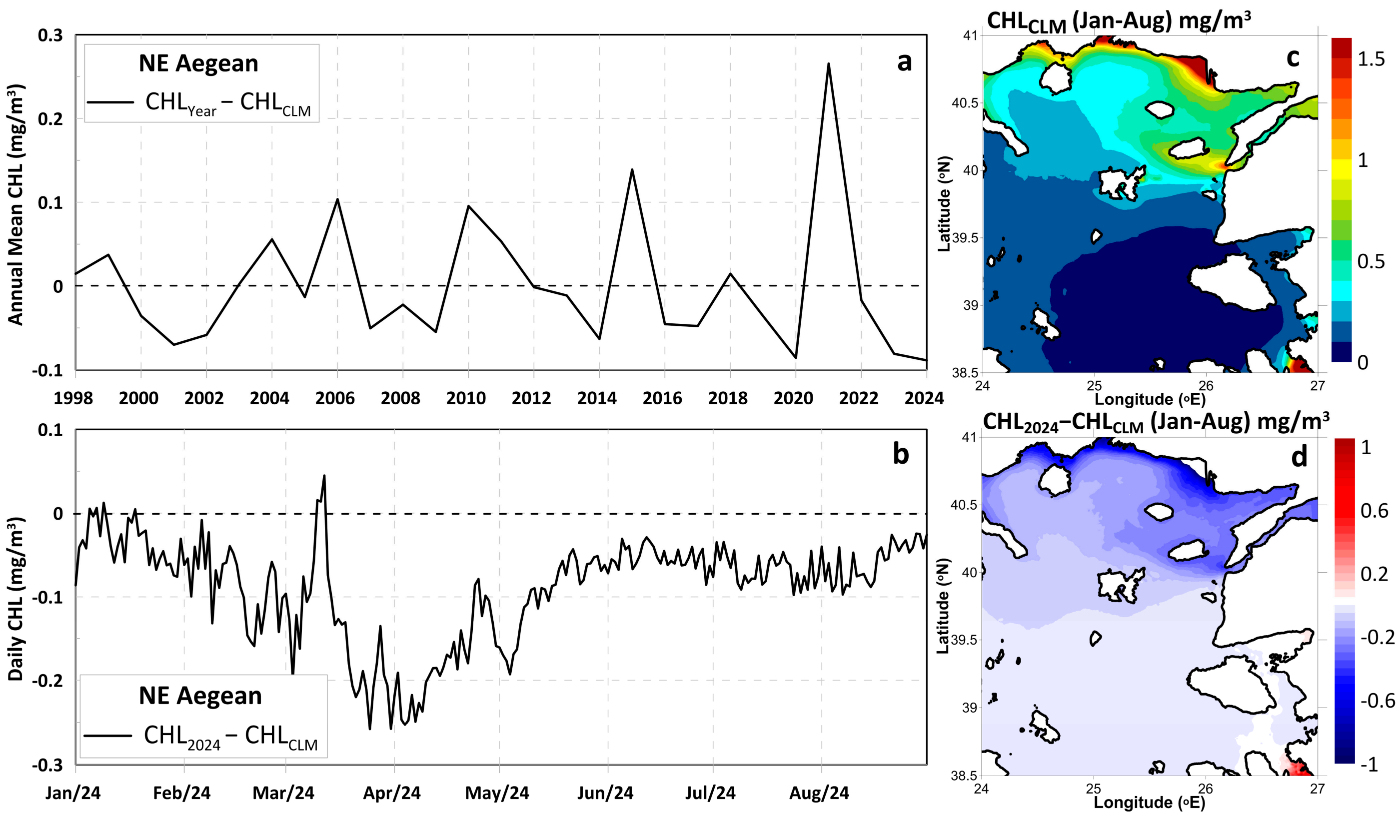

Figure 9. (**a**) Interannual difference between each year's (CHL_{Year}) and climatological (CHL_{CLM}) chlorophyll-a concentrations (mg/m^3), averaged over all daily values from January to August for the 1998–2024 period and over the Northeastern Aegean. (**b**) Daily anomaly for 2024 ($CHL_{2024} - CHL_{CLM}$). Maps of (**c**) CHL_{CLM} and (**d**) $CHL_{2024} - CHL_{CLM}$ over the Northeastern Aegean. The means for each year and the climatological values were computed over the January–August period, similar to the available 2024 time series (8 months) for comparison reasons.

4. Discussion

The exceptional mean weather conditions with very high mean air temperatures (>26 °C; Figure 5a) and a strong prevailing heat transfer budget from the atmosphere to the ocean (Figure 5c) that prevailed during the summer of 2024, following a recent multidecadal increasing interannual trend [6], influenced the respective strong increases of the sea temperature over the entire Aegean, Ionian and Cretan Seas (AICS) domain. The warmest surface waters of the last four decades (1982–2024) were detected in the AICS sub-basins during the summer months of 2024. Mean summer temperatures over 28 °C were observed over extended areas of the Ionian Sea, the South Cretan Sea, the South Dodecanese islands, and the entire North Aegean. The positive and gradually decreasing autocorrelations of the interannual sea surface temperature (SST) over the first several yearly lags indicate that rises in thermal content are entangled over multiple years, which could be due to long-term processes associated with the recorded signals of global climate change (Figure 2). The high autocorrelation at 1-year lag suggests that this warming signal is persistent year-to-year. A small amount of residual heat content seems to accumulate through the years, serving as an additional factor for the increasing temperature trends. However, the respective interannual variability of air–sea heat fluxes and other met-ocean conditions (e.g., Black Sea waters (BSW) inflow and spreading, upwelling, and other lateral exchanges with marginal seas) strongly contribute to the interannual SST fluctuation. More observational evidence of the long-term heat accumulation is required to investigate the driving factors behind this climate-related trend.

Although the number of marine heatwaves (MHWs) in the AICS in 2024 was equivalent to that of previous remarkable years (e.g., 2010 and 2018), their duration and cumulative intensity were the highest (340 days × °C) among all 43 years studied (Figure 3). They can be reasonably considered as extreme (at least for the last 43-year period) since cumulative intensity reached almost double the level of the previous maximum values (e.g., 190 days × °C in 2018). MHW durations were also considerably higher in 2024, although the analysis included only 8 months of that year (January–August). These results agree with the general pattern of the eastern Mediterranean Sea, which has fewer but longer events in comparison with the western Mediterranean [51]. Areas with very long and intense MHWs were mainly detected in the North Aegean, especially in Thermaikos Gulf (Northwestern Aegean), which has already been characterised as a hotspot of MHWs [17] with strong biological implications on its ecosystem [52].

The increased temperatures were observed not only near the surface but also in depths down to 50 m over the entire study domain and especially in its southern parts (Southwestern Aegean and Cretan Sea; Figure 4). The seawater temperatures at depths below 50 m were also high (1–3 °C higher than in previous years) during the entire year, confirming the warming of the upper ocean in most of the areas. Although the Northeastern and Central Aegean Sea remained relatively cooler in 2024 compared to other examined regions, specific areas, especially along Minor Asia, revealed a high intensity of events (Figure 3). It is noteworthy that these areas are usually colder, with weaker formation of MHWs. The mechanisms that help mitigate the adverse effects of the increasing SST over the Aegean, i.e., coastal upwelling along the East Aegean coasts and inflow of cooler BSW in the Northeastern Aegean, appear to have weakened in 2024, based on the following:

(i) Lower spreading of colder BSW over the Northeastern Aegean as deduced using surface chlorophyll-a (CHL) concentration as a proxy (Figure 9). Necessary measurements of the BSW outflow rates in the Dardanelles exit, currently not collected, would provide more specific proof of the recorded BSW reduction [26] and their contribution to the physical variability.

(ii) Although more persistent northerly winds prevailed compared to the climatology, implying stronger upwelling conditions that would prevent the formation of MHWs [53], analysis of ARGO data suggested that the upwelled water masses, originated from depths between 40 to 80 m [32,33], may have had already increased temperatures (and heat content), thus not maintaining the cooling of surface waters as effectively as in the past (Figures 4 and 8). Surface water masses with temperatures lower than 24 °C were only detected in the vicinity of the BSW exit during the summer of 2024 (Figure 7). Permanent offshore mooring stations that are currently absent over the AICS (only one offshore station is now active in the North Cretan Sea) and targeted profile measurements over the East Aegean during the summer months, when coastal upwelling occurs, may provide more insights and further explanations about the effect of this mechanism controlling the temperature levels.

The net heat flux was the main controller of the SST variability, and its anomaly with respect to climatology was positive almost everywhere in 2024 (Figure 5). Specifically, the surface net shortwave radiation, which showed a clear increasing trend over the years, is identified as the primary driver of the sea temperature variability (Figure 6), underscoring its critical role in heat gain in the upper ocean layers. The summer longwave radiation also showed an increasing trend, representing a clear reduction of heat loss from the ocean. Moreover, the heat loss from the ocean through the latent and sensible radiations was also reduced, contributing to the warming of the sea. The mixed layer (ML) temperature is strongly affected by the air–sea heat fluxes [54]. However, a more in-depth analysis of ML's variability and interannual trends over the AICS requires a larger number of ARGO floats, continuous sub-surface measurements at moorings (not currently available), or model-based studies [55].

Apart from the direct heat exchanges with the atmosphere, the near-surface temperature in the AICS is also determined by exchanges with the marginal seas. Regarding the Ionian Sea, besides the increased heat flux towards the sea (increased gain from shortwave and reduced loss from latent and longwave), inflows of warmer waters from the Adriatic and Central Mediterranean Sea contributed to the temperature rise recorded in the summer of 2024. Similarly, Levantine warm waters are also advected to the Southeastern Aegean, increasing the temperature levels there (Appendix A).

The main implications of the increased temperature levels in 2024 are physical, biological, and thus socioeconomic, affecting the coastal populations around the AICS coastal zone. The high temperature levels over the upper layers of the AICS may strengthen the stratification of the water column and extend the duration of the summer thermoclines, altering the temperature gradients, the vertical mixing, and the water masses renewal. Especially in the North Aegean, which is a source of dense waters for the entire Mediterranean Sea [27], the warmer waters that have been recently observed even during the winter months may influence the buoyancy levels and become a non-favourable condition for the initialization of dense water formations. This process may counteract the observed reduction of the BSW (Figure 9) [26], which generally results in buoyancy loss in the surface layers, serving as a favorable condition for dense water formation in the North Aegean [28,29]. Lower atmospheric temperatures will be required in the future for the formation of denser waters. Future studies should investigate the potential causes behind the observed accumulation of heat through the years in the upper ocean. In addition, warmer surface waters may affect the local climate. It is noted that the warming of the subsurface water masses in 2024 altered the characteristics of the upwelled waters, hindering their capacity to moderate coastal temperatures and create localised cooling effects that can mitigate extreme heat along coastlines.

Besides the obvious aforementioned impacts, there are several other possibly negative secondary effects (e.g., [4]), such as a drive towards mean sea level rise (due to thermal expansion of seawater) in long-term scales (e.g., [56]), a temporary intensification of storms and related surges (e.g., [57,58]), alterations of thermohaline ocean and coastal circulation (e.g., [59]), and enhancement of ocean acidification (amplifying stress on marine organisms that are vulnerable to varying pH levels) (e.g., [60]). The reduction of the solubility of oxygen due to the warming subsurface waters (e.g., deoxygenation [61]) may increase the hypoxic impacts on ocean productivity, nutrient and carbon cycling, and marine habitat [62]. Tracing specific evidence about all these implications is out of this paper's scope. Nevertheless, referring to the possible adverse effects of MHWs, especially on the marine biodiversity of Mediterranean seawater species (e.g., [63]) in coastal waters and specific gulfs of the study domain (e.g., [64]), there are several early published reports in the news sections of mass media about aquaculture mortality increase. For example, the nearly complete destruction of annual production in mussel farming activities of one of the most important farming areas in the Mediterranean (Thermaikos Gulf, with an aggregate amount of 43,000 tons of produced mussels) in the summer of 2024 due to the increased offspring mortality rates led by thermal shock, i.e., the certified local sea temperature increase, far above 30 °C [65–68]. The negative impacts on local populations also expand to next year's (2025) productivity and commercial export levels, leading to incalculable socioeconomic implications.

5. Concluding Remarks

The ocean temperature and the prevailing environmental conditions over the Aegean, Ionian, and Cretan Seas (AICS) during a 43-year period, focusing on the summer of 2024, were analyzed with the use of satellite-derived observations, field measurements, and reanalysis of atmospheric data. The main concluding remarks of the study are the following:

- The year 2024 generally showed the largest recorded sea temperatures compared to previous years. This was valid not only at the surface but also at depths down to 50 m, confirming the upper-ocean warming.
- Specifically, the summer of 2024 records showed unprecedented high temperatures across the AICS, with the warmest sea surface waters in over four decades. These were primarily driven by increased positive (downward) net heat fluxes and, therefore, net heat transfer towards the sea.
- Mean summer temperatures over 28 °C were observed over extended areas of the Ionian Sea, the South Cretan Sea, the South Dodecanese islands, and the entire North Aegean.
- A strong interannual trend (0.59 °C/decade) of the summer sea temperature was detected over the entire AICS region.
- Longer and more intensified marine heatwaves (MHWs) occurred progressively over the last four decades (>16 °C × days/decade).
- Although the number of MHW events was not abnormally increased in 2024, their duration and cumulative intensity were the highest on record, significantly impacting the ecosystem, particularly in regions like the North Aegean.
- Mechanisms that traditionally help mitigate the increase of temperatures in the Aegean Sea, such as coastal upwelling and the inflow of cooler Black Sea waters, were provenly weakened in 2024, reducing their potential cooling effects on regional seawater masses.
- The SST increasing trend through the four decades could be indicative of climate change with a persistent warming mode and possibly decadal-scale variability in the AICS's climate system, following the respective warming tendency of atmospheric temperatures.
- The rise in sea temperatures has broad physical, biological, and socioeconomic consequences, including disruptions in water stratification, reduced oxygen solubility, and significant economic losses, such as the mussel farming collapse due to thermal shock mortality of aquaculture mollusks in Thermaikos Gulf (North Greece) observed during the summer of 2024.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse12112020/s1, Maps of the net heat flux (W/m^2) anomaly for Q_s (shortwave), Q_b (longwave), Q_e (latent) and Q_h (sensible) radiations, between the summer of 2024 (Q_{2024}) and the respective climatological summer mean (Q_{CLM}) over the AICS. Positive values represent the downward radiations.

Author Contributions: Conceptualization, Y.A. and Y.K.; methodology, Y.A., V.K. and Y.K.; validation, Y.A., V.K., C.M. and Y.K.; formal analysis, Y.A. and V.K.; investigation, Y.A., V.K., Y.K. and C.M.; data curation, Y.A. and V.K.; writing—original draft preparation, Y.A., V.K., Y.K. and C.M.; writing—review and editing, Y.A., V.K., Y.K. and C.M.; visualization, Y.A. and V.K.; supervision, Y.A. and Y.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Geostrophic Circulation in the Mediterranean Sea During the Summer of 2024

To assess the horizontal transport processes between the AICS region and the marginal seas, Figure A1 presents the mean SST along with the mean surface geostrophic velocity field for the summer of 2024 in the broader Mediterranean Sea. For the derivation of the mean surface geostrophic circulation, satellite altimetry data from the L4 product 'European Seas Gridded L 4 Sea Surface Heights and Derived Variables Nrt', (SEALEVEL_EUR_PHY_L4_NRT_008_060) with daily temporal resolution and $0.125° \times 0.125°$ spatial resolution were collected from CMS (https://www.copernicus.eu/, accessed on 22 October 2024). Although accounting for the barotropic part of the water circulation only, the geostrophic components outline and highlight an important heat transport path, essential to this paper's discussion.

The SST distribution reveals a large warm pool between Italy, Greece, and Libya, while very hot waters were also detected over the Levantine Sea (Figure A1). Focusing on the broader Ionian Sea area, the main circulation patterns that prevailed in the summer of 2024 were the Western Adriatic Current (WAC), the Mid-Ionian Jet (MIJ), and the Pelops Gyre (PG), in agreement with the general circulation described by Poulain et al. [69]. The features that tend to stand out are (i) an outflow of warmer water from the Adriatic to the Ionian basin (WAC); (ii) the eastward advection of Central Mediterranean warm waters towards the East Ionian (MIJ); and (iii) the anticyclone over the South Ionian (PG) [70], which leads to convergence of warm surface masses, thus maintaining a 'patch' of warm water in that area and also advecting water masses northwards along the west coast of southern Greece. The Asia Minor Current (AMC) evolved south of Türkiye and, together with the Rhodes Gyre (RG), carried warm waters from the Levantine Sea to the southeastern part of the AICS, which also showed significantly high summer SST anomalies and high cumulative intensities of MHWs in 2024. These features contributed to the development and maintenance of the temperature characteristics that prevailed in the surface waters of the AICS region in the summer of 2024.

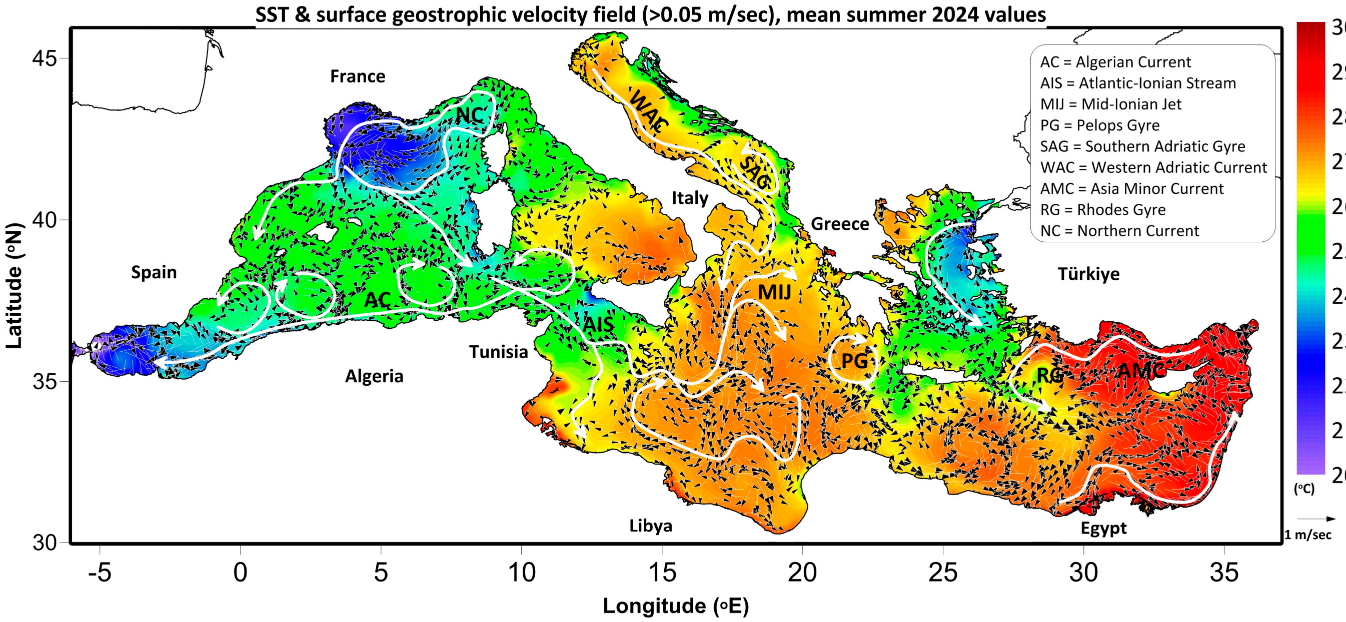

Figure A1. Mean SST and surface geostrophic circulation (only currents with speed larger than 0.05 m/s are shown) in the Mediterranean Sea in the summer of 2024. The main circulation patterns are marked with solid white lines (names derived from [69]).

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