

Article

Effect of Desert Dust Intrusion on the Detection of Marine Heatwaves

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Highlights

What is the main finding?

- Both strong and weak desert dust intrusions (when aerosol optical depth ranges within an extremely wide interval of 0.3 to 5) reduce the capability of satellite infrared radiometry to detect marine heat waves (MHWs). This was in contrast to microwave radiometry.

What is the implication of the main finding?

- The incapability of satellite infrared radiometry to detect MHWs in the presence of desert dust intrusion substantially reduces the capability of detecting MHWs by the datasets which integrate microwave and infrared radiometry of sea surface temperature. This leads to an underestimation of the presence of MHWs as an essential indicator of regional warming in the Eastern Mediterranean.

Abstract

The effect of desert dust intrusion on the detection of marine heatwaves (MHWs) has not been discussed in previous publications. In this study we investigated this effect in the Eastern Mediterranean (EM) by separate use of microwave (MW) and infrared (IR) satellite radiometry of nighttime sea surface temperature (SST); they are represented by the SST-MW and SST-IR datasets. For the first time, our analysis provides observational evidence that there was no effect of dust intrusion on the detection of MHWs by SST-MW, when aerosol optical depth (AOD) ranged within an extremely wide interval of 0.3 to 5. In contrast to SST-MW, in the presence of strong dust intrusion (AOD of up to 5), SST-IR was incapable of detecting MHWs. We found an inverse correspondence between daily variations in both SST-IR and AOD. The inverse correspondence indicates that SST-IR was profoundly influenced by desert dust, causing erroneous daily variations in SST-IR. This prevented the detection of MHWs. An essential point of our study is that even in the presence of weak dust intrusion (AOD ranged from 0.3 to 0.4) SST-IR was incapable of detecting MHWs due to the occurrence of erroneous short-term sharp drops in SST-IR. This was because of dust appearance at high altitudes. Our findings highlight that the SST-IR's incapability to detect MHWs (in the presence of dust intrusion) led to an underestimation of the presence of MHWs by the SST datasets which integrate MW and IR radiometry, i.e. the Multiscale Ultrahigh Resolution (MUR) Global Foundation SST analysis.

Keywords: marine heatwaves; desert dust; dust intrusion; satellite microwave radiometry; satellite infrared radiometry; sea surface temperature; Eastern Mediterranean Sea



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1. Introduction

Over the last few decades, a significant warming of the regional climate has been observed in the Eastern Mediterranean region [1–3], which was accompanied by the increasing warming trend of the Mediterranean Sea surface temperature (SST) by $\sim 0.4\text{ }^{\circ}\text{C decade}^{-1}$ (Figure 1a updated from [1]). This warming of the regional climate has been accompanied by a steadily increasing tendency of dust intrusions from North Africa and the Middle East [4–8]. The aforementioned regional warming has led to an increase in intensity, frequency, and spatial coverage of marine heatwaves (MHWs) in the Eastern Mediterranean Sea [9–16]. MHWs represent discrete prolonged periods of abnormally high SST which persist for five days or more, in accordance with Hobday et al. [17]. The occurrence of MHWs in the Mediterranean Sea contributes to an increase in the risk of environmental disasters causing mass-mortality events in Mediterranean marine ecosystems, including significant damage to seafood production [11,18,19]. According to Bonino et al. [16], Mediterranean summer MHWs are triggered by weak winds under subtropical ridges. When persistent subtropical ridges are established over the Mediterranean Sea, the resulting decrease in wind speeds causes a substantial reduction in latent heat loss from the sea surface [16].

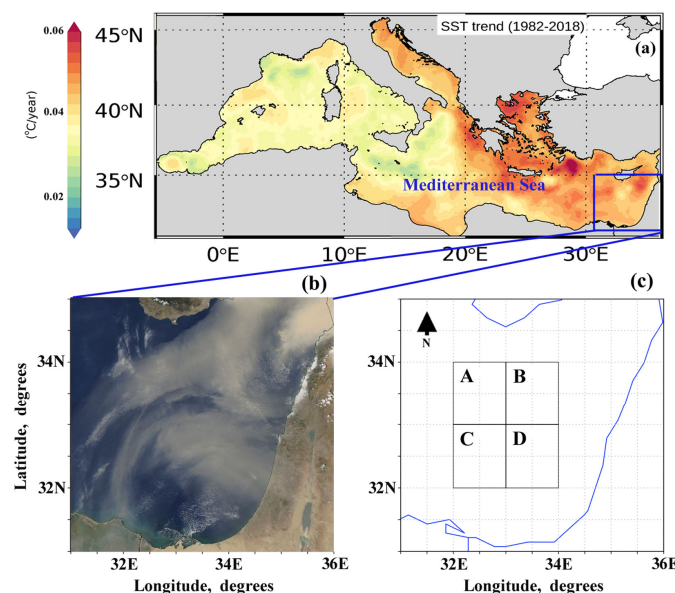


Figure 1. Maps of (a) Mediterranean SST trends (updated from Pisano et al. [1]) and (b) the Eastern Mediterranean Sea (31°N–35°N; 31°E–36°E) covered by dust intrusion on 7 September 2015. (c) Four $1^{\circ} \times 1^{\circ}$ regions selected to study the effect of dust intrusions on MHWs: A (33°N–34°N; 32°E–33°E), B (33°N–34°N; 33°E–34°E), C (32°N–33°N; 32°E–33°E), and D (32°N–33°N; 33°E–34°E).

Despite the increasing number of papers on MHW phenomena, further research is still necessary [20]. For example, little is known about the effect of desert dust intrusion on the formation of MHWs. Dust intrusions are frequently observed in the atmosphere over the Mediterranean Sea. These dust intrusions over sea areas are characterized by the arrival of warm air masses containing dust aerosols from the desert. Intensive cyclones around dust sources in the desert are responsible for Mediterranean dust intrusions [21]. Cyclonic frontal conditions cause dust penetration high into the troposphere, up to 5–6 km over the Mediterranean Sea [22,23]. The dust intrusions can produce both warming and cooling effects on the atmosphere and the sea surface below. This is because intrusions of low-altitude warm air masses from the desert contribute to air heating in the near-ground atmospheric layer, which is in contact with the sea water surface below. Moreover, dust particles absorbing shortwave solar radiation and longwave terrestrial radiation contribute to additional air heating [24–26]. On the other hand, in the daytime, dust particles could

scatter shortwave solar radiation causing a decrease in Mediterranean SST [24]. In our recent papers [27–29], we explored the impact of severe dust intrusion on surface water heating and the formation of lake heatwaves in Eastern Mediterranean lakes. According to our findings based on in situ measurements, a severe dust intrusion, which appeared in September 2015, contributed to the formation of lake heatwaves in both the hypersaline Dead Sea and freshwater Lake Kinneret. This raises the question of the possible effects of desert dust intrusion on MHWs in the Mediterranean Sea. Knowledge about such effects of dust intrusions in this area has become crucial, considering the steadily increasing tendency of dust intrusions in the eastern part of the Mediterranean Sea during the last several decades.

It is worth adding that the above-mentioned lake heatwaves in the two lakes (the Dead Sea and Lake Kinneret) were detected by in situ buoy measurements of water temperature, whereas both orbital (MODIS-Terra) and geostationary (METEOSAT) satellites were not capable of detecting those heatwaves by means of infrared (IR) radiometry of lake surface water temperature (SWT) [27–29]. Instead of an increase in lake SWT, both satellites showed a decrease, underestimating actual SWT by up to 10 °C [28,29].

Moreover, previous studies of SST in the Atlantic Ocean showed that atmospheric aerosols, and desert dust in particular, could be sources of error in SST retrievals from satellite IR radiometry [30–35]. Diaz et al. [30] discussed an increase in errors of up to ~2 °C of Advanced Very High Resolution IR Radiometer (AVHRR) Pathfinder SST retrievals in the presence of dust aerosols. Vazquez-Cuervo et al. [31] found discrepancy in SST retrievals between the Along Track Scanning Radiometer-2 (ATSR-2) microwave measurements and AVHRR IR measurements; the discrepancy varied regionally, being most significant in the Sahara dust region. In accordance with Luo et al. [32], comparisons between satellite IR radiometry of SST retrievals and SST retrievals from a ship-based IR radiometer showed that the most significant discrepancies were observed in the Saharan dust outflows. In the recent study by the same authors (Luo et al. [33]), a comparison between satellite MODIS-Terra SST observations and ship-board IR radiometry of SST showed a decrease of up to 3 degrees in MODIS SST in the presence of dust at high altitudes and an increase of up to 1 degree in MODIS SST in the presence of dust at low altitudes. All the above information indicates that desert dust particles, particularly those at high altitudes, could significantly influence SST retrievals based on satellite IR radiometry.

The effect of desert dust intrusion on the detection of MHWs has never been discussed in previous publications. In this study, for the first time, we focused on this effect in the Eastern Mediterranean by the separate use of microwave (MW) and infrared (IR) satellite radiometry of nighttime sea surface temperature (SST). Compared to MW radiometry of SST, IR radiometry of SST is much more susceptible to atmospheric dust [31–37]. Comparative analyses of MHWs, obtained by separate use of MW and IR satellite radiometry of SST, allowed us to determine the ability of IR satellite radiometry to detect MHWs in the Eastern Mediterranean, in the presence of desert dust intrusion. In addition, we assessed the ability of satellite SST datasets integrating MW and IR radiometry of SST to detect MHWs.

2. Materials and Methods

2.1. Study Area

We investigated effects of dust intrusions on MHWs in the eastern part of the Mediterranean Sea (Figure 1). It is in this area that dust intrusions are often observed, not only from the Sahara Desert in North Africa, but also from sources in the Middle East. The following four 1° × 1° zones were selected for exploring the effects of dust intrusions on marine heatwaves: A (33°N–34°N; 32°E–33°E), B (33°N–34°N; 33°E–34°E), C (32°N–33°N; 32°E–33°E), and D (32°N–33°N; 33°E–34°E) (Figure 1c). All four zones are distant from the

coastline to minimize land thermal effects. Zone C is closest to the coast of North Africa (Egypt), while zone D is closest to the coast of the Middle East (Israel).

2.2. Method

We investigated the effects of desert dust intrusions on MHWs by means of separate use of MW and IR satellite radiometry of SST. Our approach is based on the fact that IR radiometry of SST (SST-IR) is much more susceptible to atmospheric dust than MW radiometry of SST (SST-MW) [31–37]. Consequently, MHWs obtained by SST-MW retrievals were considered as actual marine heatwaves. Comparing properties of the actual MHWs with properties of the MHWs obtained by SST-IR retrievals allowed us to determine the effects of dust intrusions on SST-IR retrievals.

The time frame of this study is limited by the period of availability of the two SST datasets used in our analysis. Both the MODIS_AQUA_L3_SST_THERMAL_DAILY_9KM_NIGHTTIME_V2019.0 product and the Multiscale Ultrahigh Resolution Global Foundation SST analysis (V.4.1) of SST data have been available from 2002 until the present (Section 2.3). Therefore, this study is based on the 23-year period of satellite SST retrievals (2002–2024). Moreover, in accordance with [9], there is a seasonality to the occurrence of MHWs in the Mediterranean Sea. Based on MHW modeling, they found that surface MHWs are mainly observed from June to September [9]. Our previous studies showed that, in September, desert dust intrusions from both the Middle East sources and the Sahara Desert can be observed over the Eastern Mediterranean [8,27–29]. Based on the above information, in this study we focused on September months during the study period (2002–2024). We investigated the MHWs appearing in the specified four zones A, B, C and D (Figure 1c) in the presence of strong (September 2015) and weak (September 2020 and 2024) dust intrusions.

To determine the presence of MHWs, we applied the widely used approach suggested by Hobday et al. [17]. We conducted a comparison between day-to-day variations in SST averaged over each specified zone (A, B, C, or D) and its seasonally varying 90th percentile threshold (90th PTH). The exceedance of SST over its 90th PTH for at least five consecutive days separated by no more than one day was defined as a marine heatwave [17,38]. The seasonally varying 90th PTH was obtained for each day in September, using a running 11-day window (centered on each day from 1 to 30 September) for all of the years during the baseline period (2002–2024).

Similarly to [29], to characterize MHWs quantitatively, the following metrics were used, including start and end date, duration, maximal intensity (MI), and cumulative intensity (CI). The MHW duration was the number of consecutive days with positive anomalies of SST from its 90th PTH; the MI (°C) was the highest positive temperature anomaly value during the MHW; and the CI (°C·day) was determined as the sum of the daily anomalies during the MHW duration [29].

2.3. Data Used

To study possible effects of desert dust intrusions on MHWs in the Eastern Mediterranean, we used three datasets of nighttime SST including a SST dataset based on MW satellite radiometry, a SST dataset based on IR satellite radiometry, and a SST dataset which integrated MW and IR radiometry.

Our main SST dataset, which is based on MW radiometry, was the MW_OI-REMSS-L4-GLOB-v5.1 product, which was produced by the Group for High Resolution Sea Surface Temperature (GHRSS) at Remote Sensing Systems (REMSS) [39]. This product represents spatially gridded global nighttime SST data (version 5.1) at a horizontal resolution of 25 km × 25 km, on a daily basis. The product was produced using optimal interpolation (OI) of SST retrievals from several MW sensors, including Tropical Rainfall Measuring Mission

(TRMM) Microwave Imager (TMI); NASA Advanced Microwave Scanning Radiometer-EOS (AMSR-E); WindSat on the Coriolis satellite; Global Precipitation Measurement (GPM) Microwave Imager (GMI); and Advanced Microwave Scanning Radiometer-2 (AMSR-2) onboard the GCOM-W1 satellite [40]. During the preprocessing of this product, SST data from each of the above-mentioned MW sensors were adjusted to the daily minimum SST (just before the local sunrise) using the empirical method developed by [41]. Hereafter we will designate SST from the aforementioned product as SST-MW.

The SST dataset which is based on IR radiometry was the MODIS_AQUA_L3_SST_THERMAL_DAILY_9KM_NIGHTTIME_V2019.0 product of SST (version 2019.0), derived from the 11 and 12 μm thermal infrared (IR) bands at 01:30 local time (LT) at night [42]. This MODIS-Aqua product represents spatially gridded (L3) global SST data at a horizontal resolution of $9\text{ km} \times 9\text{ km}$ every 24 h. It is available from 2002 to the present. We chose this product as it reprocesses nighttime SST using an algorithm corrected for dust effects at night, in accordance with Luo et al. [43]. It is worth noting that the above-mentioned correction does not take into account explicit dependences on dust altitude and dust concentration [32]. Hereafter we will designate SST values from this product as SST-IR.

In addition, we used the Multiscale Ultrahigh Resolution (MUR) Global Foundation SST analysis (V.4.1), which was developed by the Group for High Resolution Sea Surface Temperature (GHRSSST). This dataset integrates nighttime SST data from satellite MW and IR observations, drifting buoy SST, and advanced optimal interpolation techniques [44]. During the preprocessing of this product, the SST data from each of the sensors used were adjusted to the daily minimum SST just before the local sunrise [41]. This dataset has a spatial resolution of $0.01^\circ \times 0.01^\circ$ and a temporal resolution of one day. It is available from 2002 to the present. Hereafter we will designate SST values from this dataset as SST-MUR.

To comprehensively study the effects of desert dust intrusion on the detection of MHWs, we used the aforementioned three SST datasets with different temperature representations: (1) SST-IR, representing temperature of the surface skin layer of 10–20 μm (which IR satellite radiometry directly observes); (2) SST-MW, representing temperature of the sub-skin layer 1 mm deep (which MW satellite radiometry directly observes); and (3) SST-MUR, representing the so-called foundation SST which is defined as the temperature of the well-mixed upper layer of a few meters deep, without strong diurnal temperature variability [35]. In this study, we assessed the ability of each of the three aforementioned SST datasets to detect MHWs in the presence of desert dust intrusion.

The vertical distribution of desert dust over the study area was obtained from the MERRA-2 aerosol reanalysis. It was produced by the NASA Global Modeling and Assimilation Office (GMAO) using the GEOS model and a modern satellite-based assimilation system [45–48]. The MERRA-2 aerosol reanalysis contains desert dust mixing ratio at 72 standard pressure levels. The dust mixing ratio is the ratio of the dust mass to the mass of air in which the dust is suspended. In his study, the dust mixing ratio is expressed in the units of $[\mu\text{g}/\text{kg}]$. The data are available all over the world, with a grid spacing of 0.5° latitude by 0.625° longitude, and a 3 h temporal resolution.

To characterize surface incoming solar radiation (SISR) in the presence of dust intrusion over the study region, we used the EO:EUM:DAT:MSG:OSI-304-D product, which is based on observations from the visible channel (0.6 μm) of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the geostationary METEOSAT satellites [49].

For this study, we used all of the datasets spatially averaged over each of the specified four zones (A, B, C, and D) (Figure 1c).

3. Results

3.1. Eastern Mediterranean SST in Warming Climate

We analyzed day-to-day variations in SST-MW in zone D in September months during the study period (2002–2024) (Figure 2). The influence of regional warming on SST-MW can be clearly seen; in particular, SST-MW was relatively low in the first five years (2002–2007); then, it gradually increased in the following years, reaching its high values in the last five years (2020–2024) (Figure 2a–d). Moreover, one can see a pronounced increase in SST-MW in September 2015 and 2020 (Figure 2e). In these two months, SST-MW was noticeably higher than SST-MW in all other September months during the study period. This illustrates the irregularity of regional warming. In this study we are going to show that marine heatwaves contributed to the high SST-MW in September 2015 and 2020.

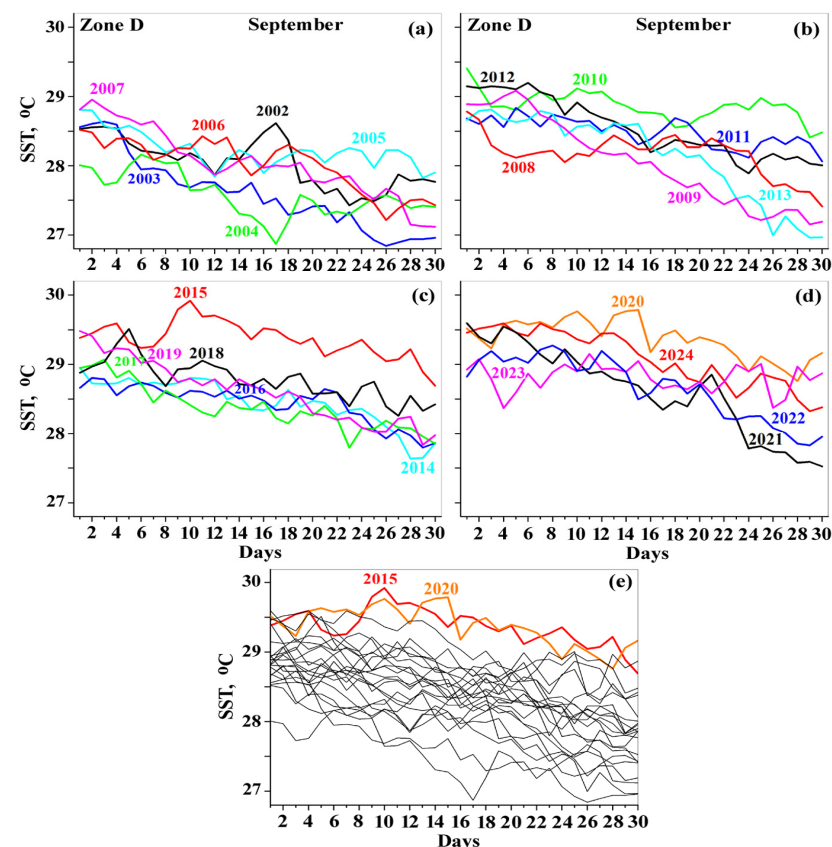


Figure 2. Day-to-day variations in SST-MW in zone D in the month of September each year during the following periods: (a) 2002–2007; (b) 2008–2013; (c) 2014–2019; and (d) 2020–2024. (e) Demonstrates the exceedance of the daily variations in SST-MW in (red) September 2015 and (orange) September 2020 over the daily variations in SST-MW in all other September months during the study period (black lines).

3.2. MHW Activity in September 2015

In this subsection we are investigating MHWs which were observed in September 2015 in the presence of a strong dust intrusion.

3.2.1. Characteristic Features of Dust Intrusions in September 2015

MODIS-Aqua satellite imagery had started showing desert dust over the Eastern Mediterranean on 7 September (Figure 3). During this dust intrusion, dust plumes originating from Syrian deserts were transported from northeast to southwest, in accordance with [50,51]. The dust intrusion peaked on 8 September: on this date the whole Eastern Mediterranean was invisible from space because of significant dust pollution. From Septem-

ber 9 to 11, the amount of dust over the Eastern Mediterranean slightly reduced. Then, from September 12 to 17, the amount of dust gradually decreased, reaching clear-sky conditions on 16–17 September 2015 (Figure 3).

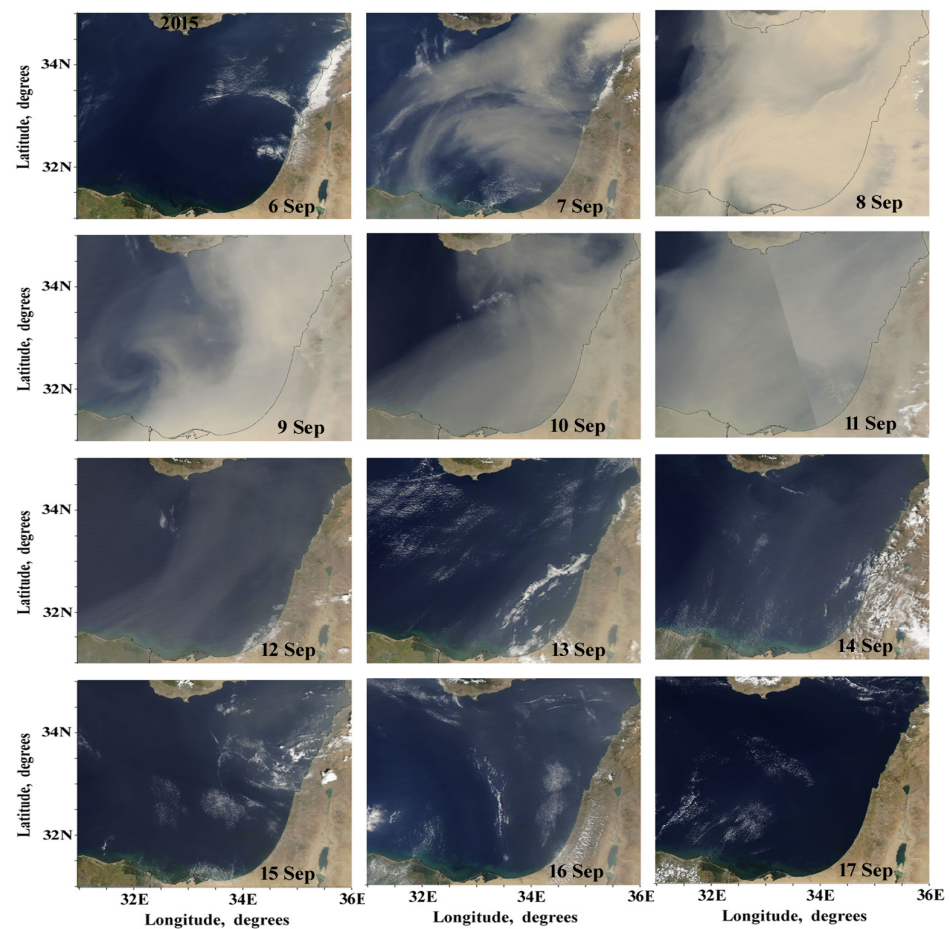


Figure 3. MODIS-Aqua imagery of the Eastern Mediterranean from 6 to 17 September 2015 at 13:30 local time (LT).

MODIS-Aqua satellite measurements of aerosol optical depth (AOD), averaged over the specified zones, showed that, on 8 September, AOD over zone A exceeded 3, while, over zones B and C, AOD values even reached ~5 (Figure 4a). There was no MODIS-Aqua AOD data over zone D due to technical reasons. The existing global operational dust prediction systems, including MERRA-2 reanalysis, were unable to correctly predict the strong dust intrusion on 8 September 2015 (Section 3.5). In this study, the missing MODIS-Aqua AOD value for zone D (32.0°N – 33.0°N ; 33.0°E – 34.0°E) on 8 September 2015 was replaced by the MODIS-Aqua AOD value (equal to 5) over the slightly modified zone D (32.0°N – 33.0°N ; 33.0°E – 34.5°E), which was extended in longitude by 0.5 degrees towards the Middle East coast (Figure 4a). The measured high AOD values on 8 September 2015 over all of the four zones indicated the presence of an extremely strong dust intrusion over the EM. From 9 to 11 September, AOD decreased, ranging from 0.7 to 1.7. A further noticeable decrease in AOD, down to 0.3, was observed from 11 to 16 September. After 16 September, AOD was mainly below 0.3 (Figure 4b).

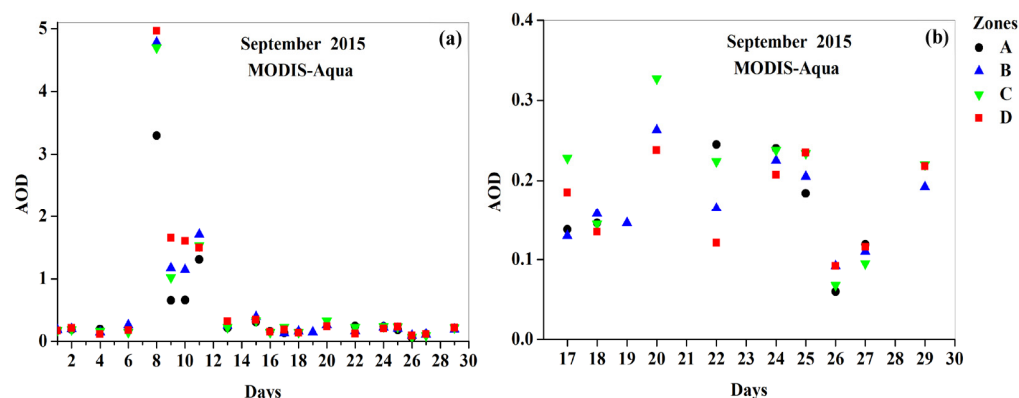


Figure 4. MODIS-Aqua satellite measurements of aerosol optical depth (AOD) averaged over the specified zones A, B, C, and D: (a) during the period from 1 to 30 September and (b) during the period from 16 to 30 September 2015.

To characterize the vertical distribution of the dust layer over the study region, we used available lidar observations from Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO). On 10 September, during its overpass of the zones B and D, CALIPSO showed that the dust layer was observed from the sea surface up to approximately 5 km altitude (Figure 5).

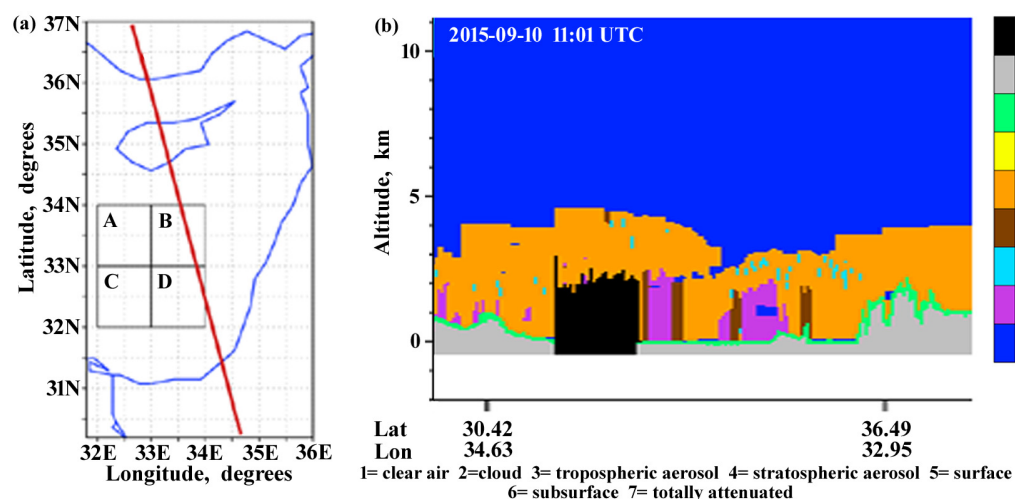


Figure 5. (a) the CALIPSO satellite overpass of the specified zones B and D in the Eastern Mediterranean and (b) its backscatter measurements of aerosols and clouds on 10 September 2015.

We analyzed the impact of the strong dust intrusion on surface incoming solar radiation (SISR) over the specified zones using METEOSAT satellite measurements of daily averaged SISR. METEOSAT showed that the dust intrusion caused a dramatic drop in SISR on 8 September in all of the specified zones simultaneously. This was due to the shortwave radiative effect of desert dust (Figure A1). To illustrate the SISR drop, we compared day-to-day variations in SISR with the baseline SISR in the months of September during the baseline period (2002–2024). In each of the specified zones, a decrease in SISR started after 6 September. On 8 September, in the presence of maximal dust pollution, SISR reached its minimum. The deepest minimum of $\sim 130 \text{ W m}^{-2}$ was observed in zone D (Figure A1). This minimum was essentially lower than the baseline SISR of $\sim 270 \text{ W m}^{-2}$ on the corresponding day. From 8 to 14 September, the SISR gradually increased, along with a decrease in AOD from 5 to 0.3 (Figure 4a). After 14 September, the SISR was within the uncertainty interval of the baseline SISR.

3.2.2. SST Spatial Distribution Changes in the Presence of Desert Dust Intrusion

Our analysis of the spatial distribution of SST-MW over the Eastern Mediterranean showed that SST-MW data were available over the study region on a daily basis during the dust intrusion (Figure 6b–e). This allowed us to obtain the characteristic features of the spatial distribution of SST-MW in the presence of dust intrusion. A noticeable east–west gradient of SST-MW was observed, with warmer waters to the eastern zones B and D. The east–west gradient significantly increased and reached its maximum during the dusty days of 9 to 10 September (Figure 6b–e). The maximal temperature difference in SST-MW (0.48°C) between zones B and A was observed on 10 September, while the maximal SST-MW difference (0.68°C) between zones D and C was observed on 9 September.

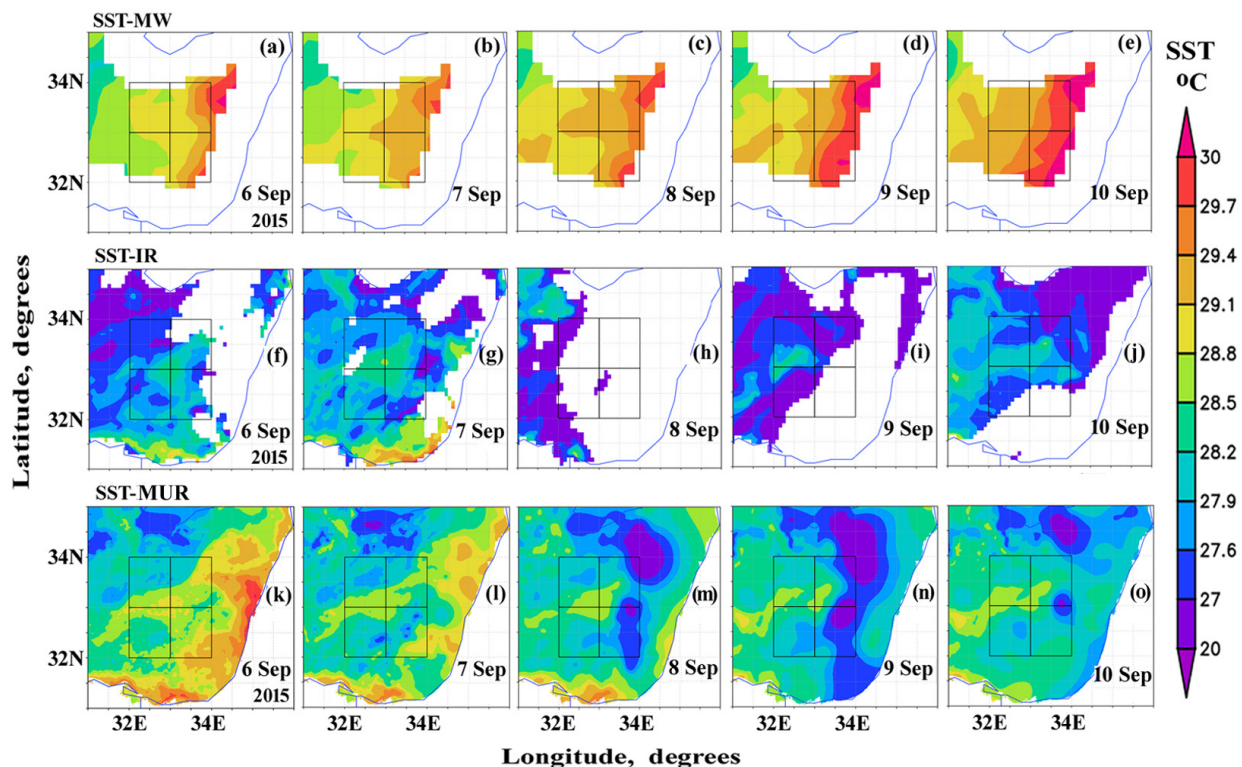


Figure 6. (Top panel)—maps of SST-MW on (a) 6 September, (b) 7 September, (c) 8 September, (d) 9 September, and (e) 10 September. (Middle panel)—maps of SST-IR on (f) 6 September, (g) 7 September, (h) 8 September, (i) 9 September, and (j) 10 September. (Bottom panel)—maps of SST-MUR on (k) 6 September, (l) 7 September, (m) 8 September, (n) 9 September, and (o) 10 September 2015.

Now we are going to present evidence of the incorrect spatial distribution of SST provided by IR radiometry in the presence of strong dust intrusion. In particular, spatial distributions of SST-IR over the same study region showed east–west gradients which were opposite to those of the SST-MW spatial distribution. From 7 to 10 September, spatial distributions of SST-IR showed the east–west gradients with warmer waters to the western zones A and C (Figure 6g–j). This indicates a lack of correspondence between the SST-IR spatial distribution and the SST-MW spatial distribution in the presence of the dust intrusion. After the disappearance of the dust intrusion, from 17 to 21 September, the spatial distribution of SST-IR showed the east–west gradients with warmer water to the eastern zones B and D (Figure 7f–j), which were similar to the east–west gradients based on SST-MW (Figure 7a–e).

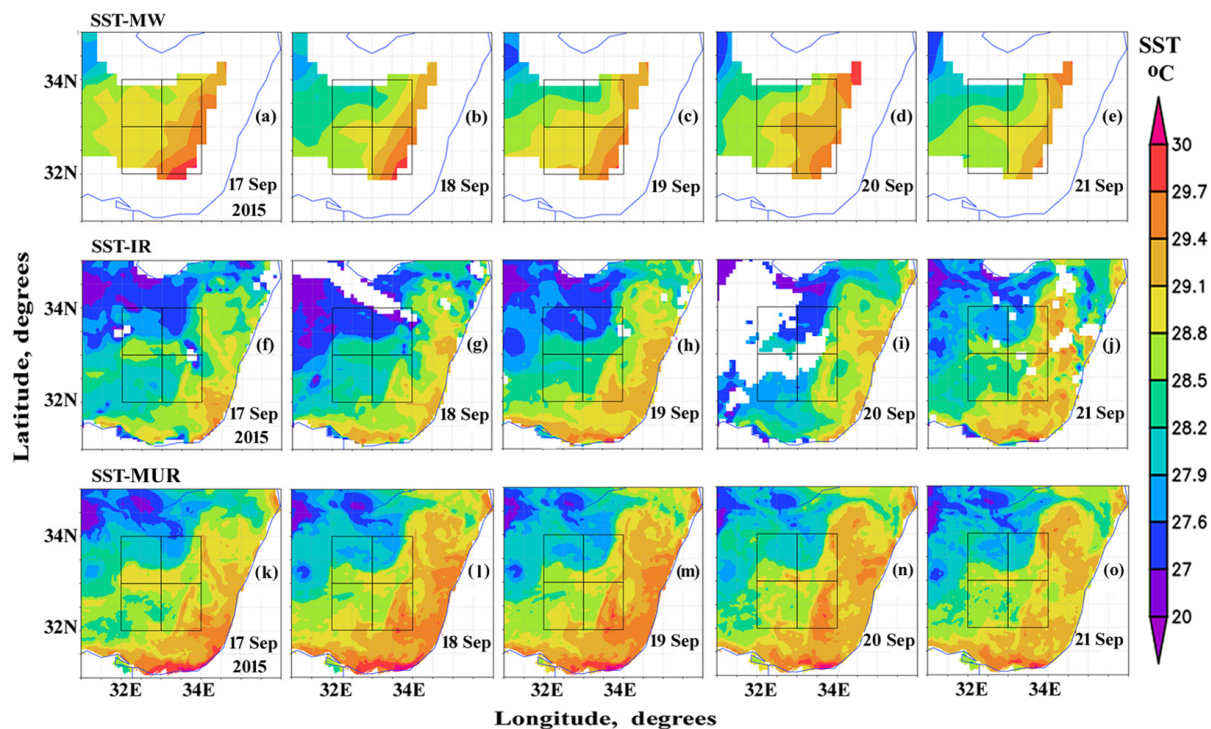


Figure 7. (Top panel)—maps of SST-MW on (a) 17 September, (b) 18 September, (c) 19 September, (d) 20 September, and (e) 21 September. (Middle panel)—maps of SST-IR on (f) 17 September, (g) 18 September, (h) 19 September, (i) 20 September, and (j) 21 September. (Bottom panel)—maps of SST-MUR on (k) 17 September, (l) 18 September, (m) 19 September, (n) 20 September, and (o) 21 September 2015.

In addition, we analyzed the spatial distribution of SST-MUR over the Eastern Mediterranean in the presence of the strong dust intrusion (Figure 6l–o). As mentioned, the SST-MUR dataset integrates SST data from satellite MW and IR radiometry. Our analysis provides evidence that, in the presence of the strong dust intrusion, the spatial distribution of SST-MUR over the Eastern Mediterranean was incorrect. In particular, from 8 to 10 September 2015, the SST-MUR spatial distribution showed east–west gradients with warmer water to the wester zones A and C (Figure 6l–o); these gradients did not reflect the true east–west gradients as observed by the SST-MW spatial distribution (Figure 6b–e). However, from 17 to 21 September, after the disappearance of the dust intrusion, the spatial distribution of SST-MUR showed the correct east–west gradients with warmer water to the eastern zones B and D (Figure 7k–o), which were similar to the east–west gradients based on SST-MW (Figure 7a–e).

3.2.3. MHWs in September 2015

To detect MHWs in September 2015, we compared daily variations in both SST-MW and its 90th PTH in each of the specified zones. Our analysis clearly showed the formation of abnormally high SST-MWs during prolonged periods of more than five consecutive days, when SST-MW exceeded its seasonally varying 90th PTH in each of the four specified zones (Figure 8a–d). All four zones (A, B, C, and D) experienced MHWs. This illustrates the large scale of this phenomenon observed in September 2015 in the EM.

Based on SST-MW, we observed MHWs with a 20-day duration; this included not only 10 dusty days from 7 to 16 September, but also several days after the disappearance of this dust intrusion when AOD was lower than 0.3 (Figure 8). This indicates that desert dust particles were not a causal factor for the MHWs observed in September 2015, but rather the MHWs were caused by the arrival of warm air masses from the desert.

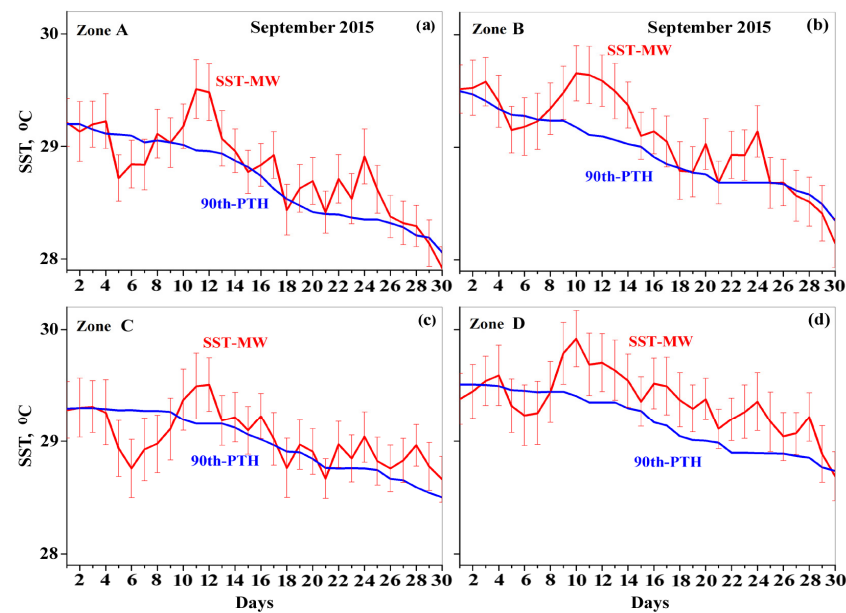


Figure 8. Comparison between day-to-day variations in SST-MW in September 2015 and its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The vertical lines designate the uncertainty of SST-MW.

To characterize quantitatively the properties of the observed MHWs in each of the specified zones, we obtained their metrics using the anomalies of SST-MW from its seasonally varying 90th-PTH. Table 1 represents the start and end dates, duration, maximal intensity (MI), and cumulative intensity (CI) of the observed MHWs. The MHW with the longest duration of 22 days (8–29 September) was observed in zone D, the closest to the coast of the Middle East. Its MI was approximately 0.5°C and its CI was equal to $\sim 6^{\circ}\text{C}\cdot\text{day}$. The MHW with the lowest MI of $\sim 0.3^{\circ}\text{C}$ was observed in zone C, the most distant from the coast of the Middle East (Table 1).

Table 1. The metrics of the MHWs based on the following datasets: the SST-MW anomalies, the SST-IR anomalies, and the SST-MUR anomalies in the specified four zones in the EM in September 2015. In each zone, the MHW metrics include the start and end dates, duration, maximal intensity (*MI*) and cumulative intensity (*CI*). Note that in zone C two separate MHWs occurred.

Zone	Start Date	End Date	Duration, Days	MI, $^{\circ}\text{C}$	CI, $^{\circ}\text{C}\cdot\text{Day}$
SST-MW anomalies					
A	8 September	28 September	21	0.56	3.70
B	8 September	26 September	19	0.53	4.37
C	10 September	17 September	8	0.35	1.49
C	22 September	30 September	9	0.37	1.70
D	8 September	29 September	22	0.51	6.22
SST-IR anomalies					
A	23 September	27 September	5	0.42	1.23
B	-	-	-	-	-
C	21 September	28 September	8	0.60	2.33
D	18 September	28 September	11	0.94	4.04

Table 1. *Cont.*

Zone	Start Date	End Date	Duration, Days	MI, °C	CI, °C·Day
SST-MUR					
A	-	-	-	-	-
B	-	-	-	-	-
C	17 September	21 September	5	0.22	0.78
C	24 September	29 September	6	0.31	1.39
D	16 September	30 September	15	0.50	4.29

Compared to SST-MW, SST-IR is much more susceptible to atmospheric dust. We are going to show that this sensitivity limits its ability to detect MHWs. Indeed, in all specified zones, on dusty days from 6 to 8 September, when an increase in dust intrusion was characterized by an increase in AOD from 0.3 to 5, SST-IR values decreased by up to 4 °C (Figure 9). From 8 to 16 September, when a decrease in dust intrusion was characterized by a decrease in AOD from 5 to 0.3, SST-IR gradually increased (Figure 9). The aforementioned decrease and subsequent increase in SST-IR on dusty days is evidence of a strong effect of the dust intrusion on satellite IR radiometry of SST causing erroneous daily variations in SST-IR retrievals (Section 3.5). As a result, these daily variations in SST-IR were incapable of reproducing the MHWs, which were detected by SST-MW in the presence of dust intrusion.

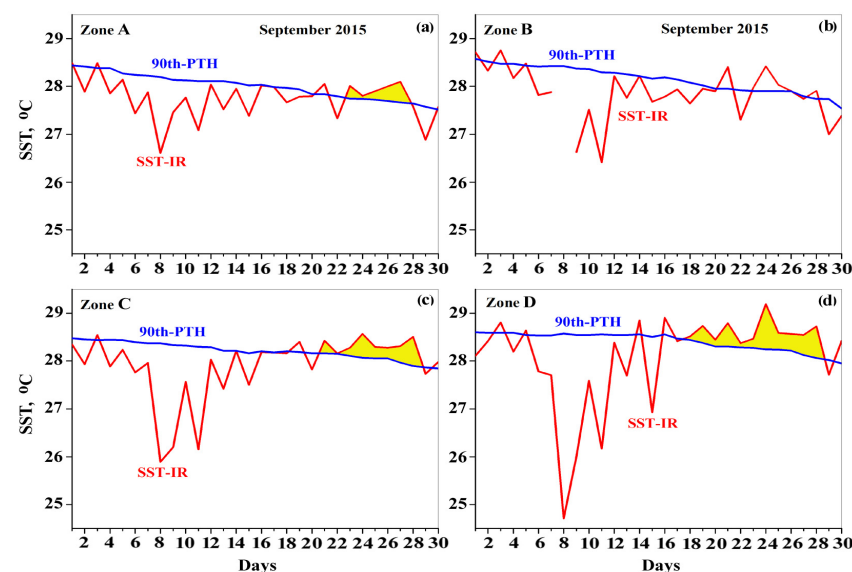


Figure 9. A comparison between the (red lines) daily variations in SST-IR in September 2015 and the (blue lines) daily variations in its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The yellow color designates the MHWs detected by SST-IR.

However, after the disappearance of the dust intrusion, daily variations in SST-IR showed a totally different picture. In three zones (A, C, and D), the presence of MHWs was detected when SST-IR exceeded its seasonally varying 90th PTH. Specifically, in zone A, SST-IR displayed a MHW with a 5-day duration (23–27 September), MI equal to 0.4 °C, and CI equal to ~1 °C·day; in zone C, it displayed a MHW with a 8-day duration (21–28 September), MI of 0.6 °C, and CI of 2 °C·day; in zone D, it displayed a MHW with a 11-day duration (18–28 September), MI of ~0.9 °C, and CI of 4 °C·day (Figure 9 and Table 1). No MHW was detected in zone B. Our analysis showed that in the presence of a strong dust intrusion (AOD of up to 5) in September 2015 the CI of the MHWs detected by SST-IR was essentially lower than the CI of the MHWs detected by SST-MW (Table 1).

Our analysis showed that the failure of IR radiometry to detect MHWs in the presence of the strong dust intrusion substantially reduced the ability to detect MHWs by the SST-MUR dataset integrating MW and IR radiometry. In particular, we found that SST-MUR was also incapable of detecting MHWs in each of the four zones from 7 to 16 September (Figure 10a–d). However, from 17 to 30 September 2015, after the disappearance of the strong dust intrusion, SST-MUR showed the presence of MHWs in zones C and D (Figure 10). In zone C, MHWs were observed during two periods: from 17 to 21 September and from 24 to 29 September (11 days in total) with MI of 0.2 °C and 0.3 °C, respectively. In zone D, a longer MHW was observed, during the 15-day period from 16 to 30 September, with MI of 0.5 °C and CI of 4.3 °C·day (Table 1). No MHWs were detected by SST-MUR in zones A and B.

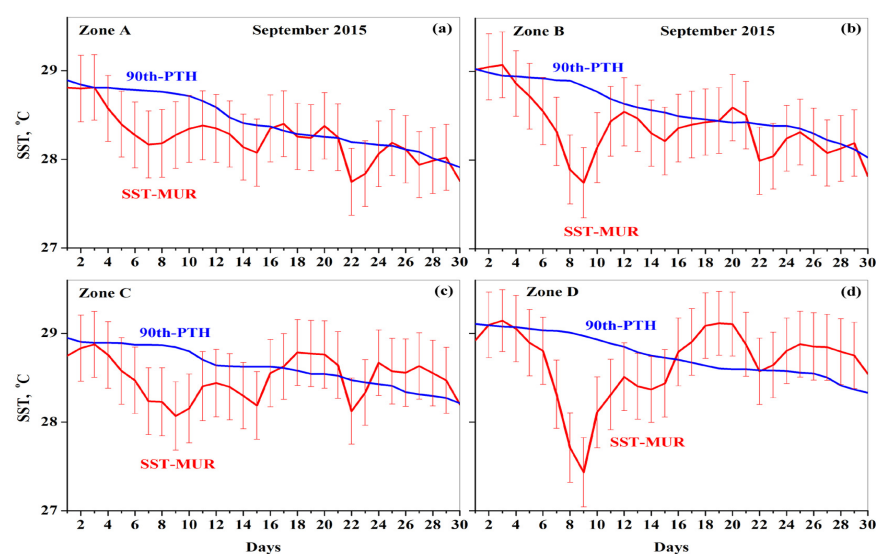


Figure 10. Comparison between the (red lines) daily variations in SST-MUR in September 2015 and the (blue lines) daily variations in its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The vertical lines designate the uncertainty of SST-MUR.

3.3. MHW Activity in September 2020

In this section we investigate MHWs during September 2020, in the presence of a weak dust intrusion. During the first decade of September 2020, the dust intrusion was characterized by AOD ranging between 0.3 and 0.4 (Figure 11). During the second and third decades of September 2020, AOD was mainly lower than 0.3, except for 17 and 18 September when AOD reached 0.32 and 0.34, respectively.

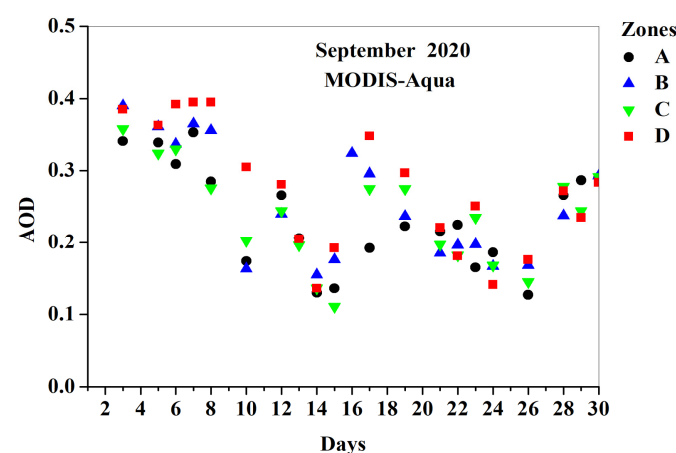


Figure 11. MODIS-Aqua satellite measurements of AOD averaged over specified zones A, B, C, and D in September 2020 at 13:30 LT.

Starting from 4 September 2020, SST-MW showed the formation of long-term MHWs in each of the four zones, when SST-MW exceeded its seasonally varying 90th PTH during a 20-day period (Figure 12a–d). The MHW with the longest duration, of 24 days (4–27 September), was observed in zone D, while the MHW with the shortest duration, of 20 days (4–23 September), was observed in zone B (Table 2).

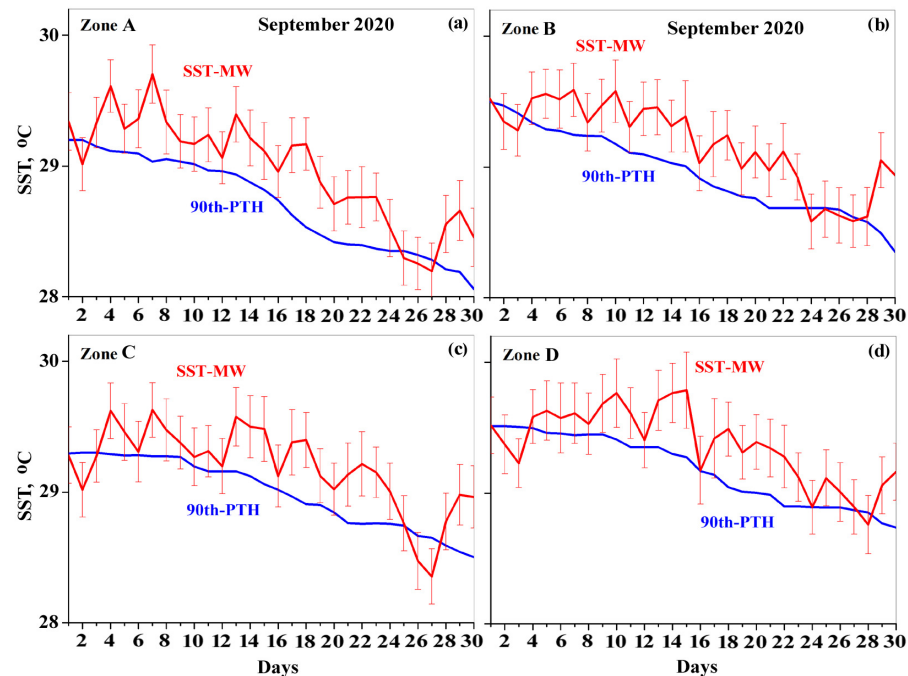


Figure 12. A comparison between daily variations in SST-MW in September 2020 and its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The vertical lines designate the uncertainty of SST-MW.

In contrast to SST-MW, SST-IR failed to show MHWs during the first decade of September 2020 (Figure 13). Instead of a prolonged period of abnormally high SST, on those days (1–10 September), SST-IR exhibited the appearance of short-term sharp drops on some days, which did not reflect the true daily variations in actual SST. As a result, SST-IR was incapable of detecting MHWs during the first decade of September 2020 (Figure 13 and Table 2).

Table 2. The metrics of MHWs in the specified four zones in the Eastern Mediterranean in September 2020. In each zone, the MHW metrics include the start and end dates, duration, maximal intensity (MI), and cumulative intensity (CI).

Zone	Start Date	End Date	Duration, Days	MI, °C	CI, °C·Day
SST-MW anomalies					
A	3 September	24 September	22	0.66	7.23
B	4 September	23 September	20	0.43	5.76
C	4 September	25 September	22	0.49	5.58
D	4 September	27 September	24	0.51	5.61
SST-IR anomalies					
A	13 September	23 September	11	0.88	3.63
B	11 September	15 September	5	0.44	1.38
C	-	-	-	-	-
D	11 September	16 September	6	0.31	0.72

Table 2. Cont.

Zone	Start Date	End Date	Duration, Days	MI, °C	CI, °C·Day
SST-MUR					
A	8 September	25 September	18	0.50	3.89
B	8 September	14 September	7	0.30	1.53
B	17 September	22 September	6	0.26	0.96
C	8 September	30 September	23	0.45	6.11
D	8 September	14 September	7	0.46	2.04
D	17 September	30 September	14	0.36	2.26

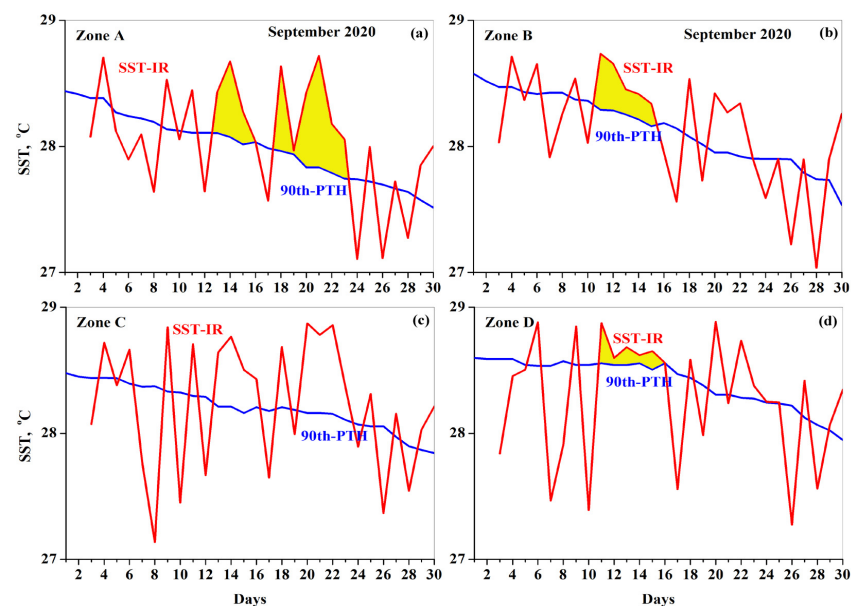


Figure 13. A comparison between daily variations in SST-IR in September 2020 and its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The yellow colors designate the detected MHWs.

During the subsequent period from 11 to 22 September 2020, SST-IR showed the occurrence of abnormally high values in zones A, B, and D. However, sharp drops in the SST-IR on some days prevented the identification of long-lasting MHWs. Instead, SST-IR showed the formation of short-term MHWs with a duration of only 5–6 days in zones B and D (Figure 13b,d). In zone A, we can assume the formation of a marine heatwave lasting 11 days (13–23 September), if we ignore the SST-IR drop on 16 September 2020. In zone C, abnormally high SST-IR values were observed for 3–4 consecutive days, followed by days with sharp drops in SST-IR. This does not exactly correspond to the criteria for the formation of a marine heatwave, which requires five consecutive days with an abnormally high SST-IR (Section 2.2).

Our analysis showed that, even in the presence of weak dust intrusion, the incapability of SST-IR to detect MHWs reduced the capability of the SST-MUR dataset integrating MW and IR radiometry to detect MHWs. In particular, SST-MUR was incapable of detecting MHWs before 8 September 2020 (Figure 14 and Table 2), in contrast to SST-MW. Although, starting from 8 September, SST-MUR showed long-term MHWs in each of the four zones. The longest MHW, with a duration of 23 days (8–30 September) and MI of 0.4 °C, was observed in zone C (Table 2). In zones B and D, SST-MUR showed the presence of two consecutive MHWs in September 2020. Specifically, in zone B, MHWs were observed from

8 to 14 September and from 17 to 22 September. Similarly, in zone D, MHWs were observed from 8 to 14 September and from 17 to 30 September (Table 2 and Figure 14).

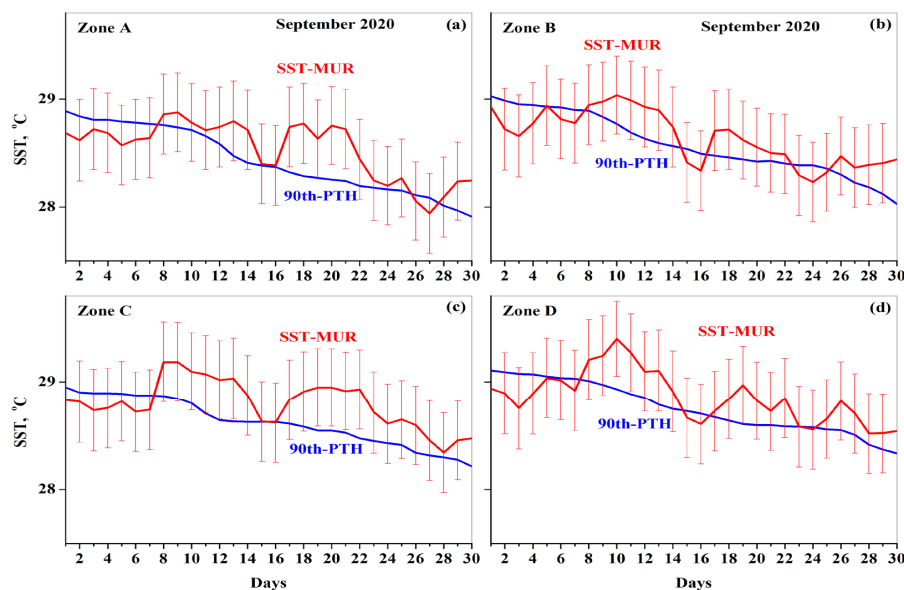


Figure 14. A comparison between day-to-day variations in SST-MUR in September 2020 and its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The vertical lines designate the uncertainty of SST-MUR.

3.4. MHW Activity in September 2024

In this section we investigate MHWs which were observed from 1 to 18 September 2024 in the absence of dust intrusion, when AOD was mainly lower than 0.3 in each zone (Figure 15).

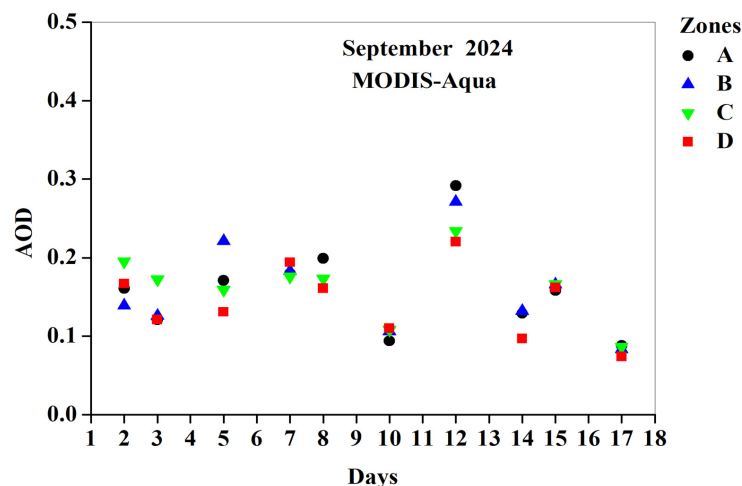


Figure 15. MODIS-Aqua satellite measurements of AOD averaged over specified zones A, B, C, and D, from 1 to 18 September 2024.

Our analysis showed that, in the absence of dust intrusion, SST-MW and SST-IR showed similarities in their identification of the occurrence of marine heatwaves in September 2024. Specifically, both SST-MW and SST-IR showed the formation of MHWs in zones A, C, and D, whereas no MHWs were observed in zone B (Figures 16 and 17). It is worth noting that, in the absence of dust intrusion ($AOD < 0.3$), in zone A and especially in zone D, SST-IR showed MHWs more clearly and with greater intensity than SST-MW (Figures 16 and 17). Even in the absence of dust intrusion, one can see the appearance

of short-term sharp drops in SST-IR from time to time (Figure 17a–d). However, these occasional sharp drops in SST-IR did not prevent the detection of MHWs.

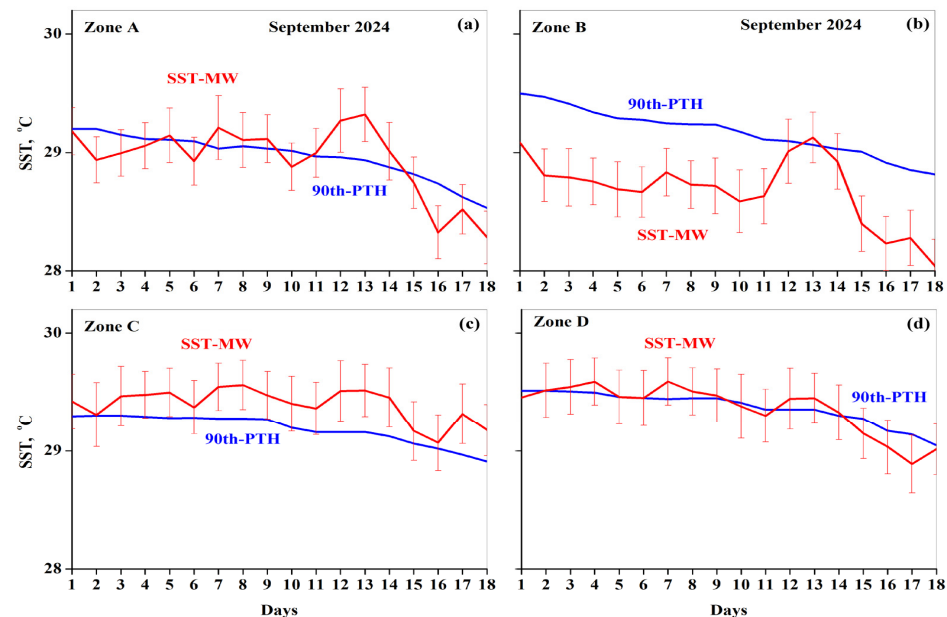


Figure 16. A comparison between day-to-day variations in SST-MW in September 2024 and its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The vertical lines designate the uncertainty of SST-MW.

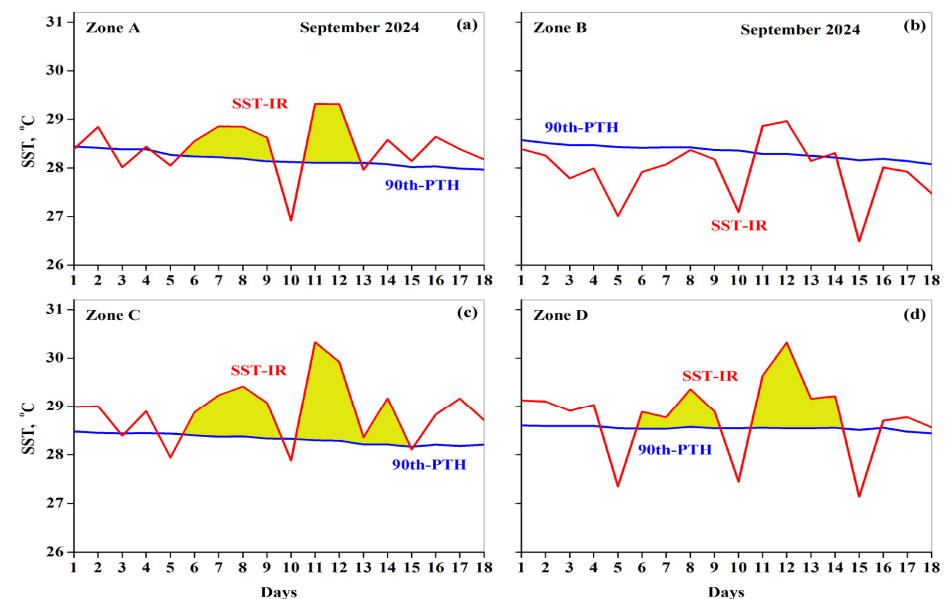


Figure 17. A comparison between daily variations in SST-IR in September 2024 and its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The yellow colors designate the detected MHWs.

Our analysis of the SST-MUR dataset (integrating MW and IR radiometry) showed that, in the absence of dust intrusion (1–18 September 2024), SST-MUR detected pronounced MHWs in three zones: A, C, and D, similarly to SST-MW and SST-IR (Figure 18). SST-MUR showed no MHWs in zone B (Table 3).

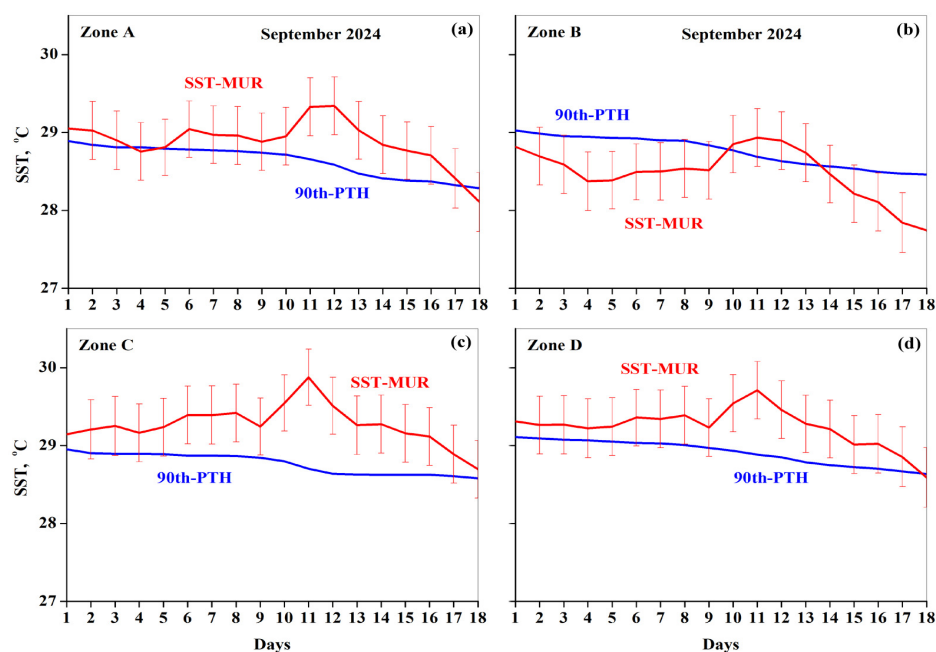


Figure 18. A comparison between daily variations in SST-MUR in September 2024 and its seasonally varying 90th PTH in (a) zone A, (b) zone B, (c) zone C, and (d) zone D. The vertical lines designate the uncertainty of SST-MUR.

Table 3. The metrics of the MHWs in the specified four zones in the Eastern Mediterranean in September 2024. In each zone, the MHW metrics include the start and end dates, duration, maximal intensity (*MI*), and cumulative intensity (*CI*).

Zone	Start Date	End Date	Duration, Days	<i>MI</i> , °C	<i>CI</i> , °C·Day
SST-MW anomalies					
A	7 September	14 September	8	0.38	1.00
B	-	-	-	-	-
C	2 September	18 September	17	0.35	3.64
D	2 September	9 September	8	0.14	0.36
SST-IR anomalies					
A	6 September	12 September	7	1.20	3.30
B	-	-	-	-	-
C	6 September	15 September	10	2.00	7.40
D	6 September	14 September	9	1.80	4.75
SST-MUR					
A	5 September	17 September	13	0.75	4.28
B	-	-	-	-	-
C	1 September	18 September	18	1.17	8.94
D	1 September	17 September	17	0.82	5.97

3.5. Incorrect SST-IR Retrievals in the Presence of Desert Dust Intrusion

In the presence of a strong dust intrusion (7–16 September 2015), a comparative analysis of daily variations in the anomalies of SST-MW and SST-IR from their seasonally varying 90th PTH showed an essential difference between them (Figure 19a). Now, we focus on zone D, the closest to the coast of the Middle East.

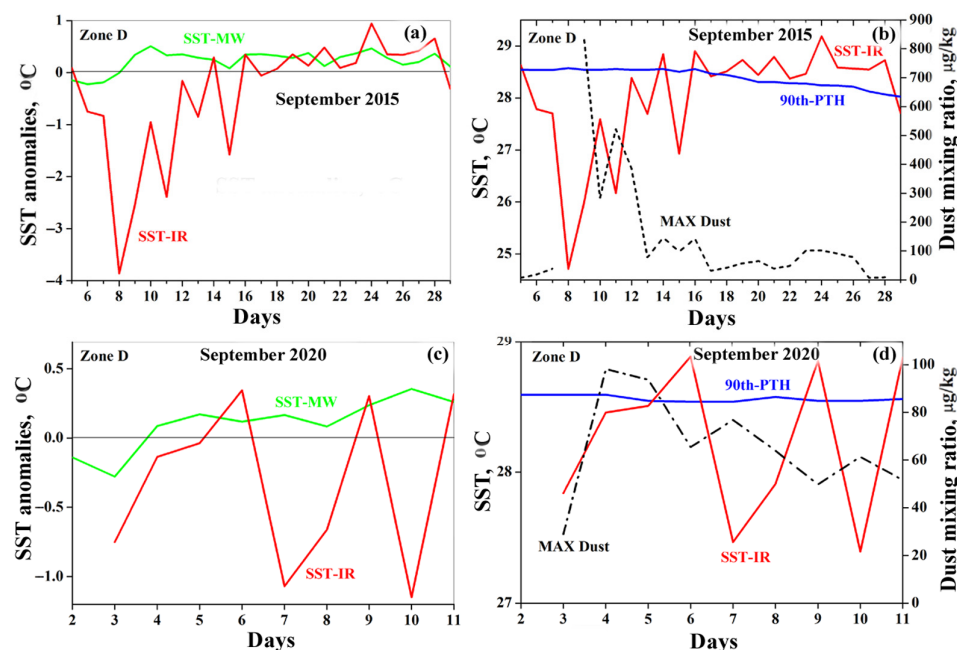


Figure 19. (a) A comparison between the day-to-day variations in (red line) the SST-IR anomalies and in (green line) the SST-MW anomalies during the period from 5 to 29 September 2015, in zone D. (b) Comparison between the day-to-day variations in (red line) SST-IR and (black dashed line) maximal dust mixing ratio (MAX Dust). MERRA2 showed an erroneous MAX Dust on 8 September 2015. This is the reason for not showing the erroneous MAX Dust value in this Figure. (c) A comparison between the day-to-day variations in (red line) the SST-IR anomalies and in (green line) the SST-MW anomalies during the period from 2 to 11 September 2020, in zone D. (d) Comparison between the day-to-day variations in (red line) SST-IR and (black shaded line) maximal dust mixing ratio (MAX Dust).

Our analysis provides evidence that, even in the presence of a strong dust intrusion (AOD ranged from 0.3 to 5), there was no relationship between daily variations in SST-MW anomalies from its 90th PTH and daily variations in AOD. Starting from 8 September 2015, the SST-MW anomalies were positive, indicating the appearance of a MHW characterized by abnormally high SST-MW (Figure 19a). The absence of any relationship (between daily variations in SST-MW anomalies and daily variations in AOD) indicated that there was no effect of the strong dust intrusion on the detection of MHWs by SST-MW.

However, during the same period, the daily variations in the SST-IR anomalies from its 90th PTH were completely different: they were negative on dusty days from 7 to 16 September 2015 (Figure 19a). A comparative analysis has been conducted between daily variations in SST-IR and maximal dust mixing ratio (MAX Dust) (Figure 19b). MAX Dust was obtained using the vertical distribution of dust mixing ratio based on MERRA2 aerosol reanalysis. Note that existing global operational dust prediction systems were unable to correctly predict the strong dust intrusion on 8 September 2015 [50,51]. In particular, the MERRA2 reanalysis erroneously showed that MAX Dust on 8 September ($200 \mu\text{g/kg}$) was lower than MAX Dust on the subsequent dusty days from 9 September ($800 \mu\text{g/kg}$) to 12 September ($400 \mu\text{g/kg}$) (Figure 19b). This is the reason for not showing the erroneous MAX Dust value on 8 September in Figure 19b.

From 6 to 8 September 2015, SST-IR decreased by approximately $\sim 4^\circ\text{C}$ (Figure 19b). This decrease in SST-IR from 6 to 8 September 2015 was accompanied by the appearance of a strong dust intrusion characterized by an increase in AOD from 0.3 to 5. The aforementioned decrease in SST-IR was followed by a gradual increase in SST-IR from 8 to 16 September 2015 (Figure 19b). This increase in SST-IR from 8 to 16 September 2015 was accompanied by the weakening of the dust intrusion characterized by a decrease in MAX

Dust from 800 to 100 $\mu\text{g}/\text{kg}$ (and by a decrease in AOD from 5 to 0.3) (Figure 19b). Therefore, our analysis provides evidence of an inverse correspondence between SST-IR and MAX Dust; an increase in MAX Dust was accompanied by a decrease in SST-IR and a subsequent decrease in MAX Dust was accompanied by an increase in SST-IR. This inverse correspondence indicated that in the presence of a strong dust intrusion (7–16 September 2015) the MODIS-Aqua IR radiometry was essentially influenced by atmospheric dust, causing erroneous SST-IR retrievals. As a result, in the presence of the strong dust intrusion, daily variations in SST-IR anomalies differed from daily variations in SST-MW anomalies (Figure 19a).

Previously we emphasized a decrease in SST-IR of up to 4 $^{\circ}\text{C}$, which was associated with the strengthening of a strong dust intrusion. Now, we wish to show that even a weak dust intrusion could cause sharp drops in SST-IR. In particular, on 15 September 2015, in the presence of a weak dust intrusion characterized by AOD equal to 0.34, a sharp drop in SST-IR of ~ 1.5 $^{\circ}\text{C}$ was observed in zone D (Figure 19b). This sharp drop in SST-IR was observed in comparison to SST-IR on the previous day: 14 September 2015 (Figure 19b). Note that the sharp drop in the SST-IR anomalies on 15 September 2015 did not reflect the true behavior of actual SST, as proved by the positive SST-MW anomalies on that day (Figure 19a).

Similarly, from 2 to 10 September 2020, in the presence of a weak dust intrusion characterized by AOD ranging from 0.3 to 0.4, sharp drops in SST-IR anomalies were observed on 7 and 10 September 2020 (Figure 19c). The aforementioned two sharp drops were observed in comparison to SST-IR anomalies on the days preceding the SST-IR drops: 6 and 9 September 2020. These two sharp drops in SST-IR were the reason for the appearance of negative SST-IR anomalies in the first decade of September 2020 (Figure 19c). As a result, SST-IR was incapable of detecting MHWs. Unlike SST-IR, the positive SST-MW anomalies showed MHWs in the first decade of September 2020 in the presence of the weak dust intrusion (Figure 19c). It is worth noting that, even in the presence of this weak dust intrusion, our comparative analysis showed weak inverse relationships between SST-IR and MAX Dust. In particular, the local minima of MAX Dust on 6 and 9 September 2020 were accompanied by the local maxima in SST-IR, while the local maxima in MAX Dust on 7 and 10 September were accompanied by the local minima in SST-IR (Figure 19d).

To investigate causal factors responsible for the formation of the aforementioned sharp drops in SST-IR in the presence of a weak dust intrusion, we analyzed the statistical distribution of SST-IR values for three one-day periods: 14 and 15 September 2015, 6 and 7 September 2020, and 9 and 10 September 2020. The statistical distribution of SST-IR values on each day was created by means of the GRADS software (Version 2.2.1.oga.1) [52] using the SST-IR values for 196 pixels in zone D (Figure 20).

We found that the statistical distribution of SST-IR on the days preceding the SST-IR drops was different from the statistical distribution of SST-IR on the days of the SST-IR sharp drops. For example, on 14 September 2015, the statistical distribution of SST-IR was monomodal with a single peak between 28.5 and 29.0 $^{\circ}\text{C}$ (Figure 20a) and SST-IR ranged within a narrow interval (27.5–30.0 $^{\circ}\text{C}$). In contrast, on 15 September 2015, in the presence of a SST-IR drop, the statistical distribution of SST-IR was almost flat, without any distinct mode, and SST-IR ranged within a wider interval (25.5–29.5 $^{\circ}\text{C}$) than on 14 September (Figure 20b). Similarly, on 6 September 2020, the statistical distribution of SST-IR was monomodal with a single peak between 28.5 and 29.0 $^{\circ}\text{C}$ and SST-IR ranged within a narrow interval (27.0–29.5 $^{\circ}\text{C}$) (Figure 20c). In contrast, on 7 September 2020, in the presence of a SST-IR drop, the statistical distribution of SST-IR was flat and SST-IR ranged within a wider interval (25.5–29.5 $^{\circ}\text{C}$) than on 6 September (Figure 20d). Finally, on 9 September 2020, the statistical distribution of SST-IR was monomodal with a single peak between

28.5 and 29.0 °C, and SST-IR ranged within an interval of 27.5–30.0 °C (Figure 20e). In contrast, on 10 September 2020, in the presence of an SST drop, the statistical distribution of SST-IR was flat, and SST-IR ranged within a wider interval (26.0–28.5 °C) than on 9 September (Figure 20f).

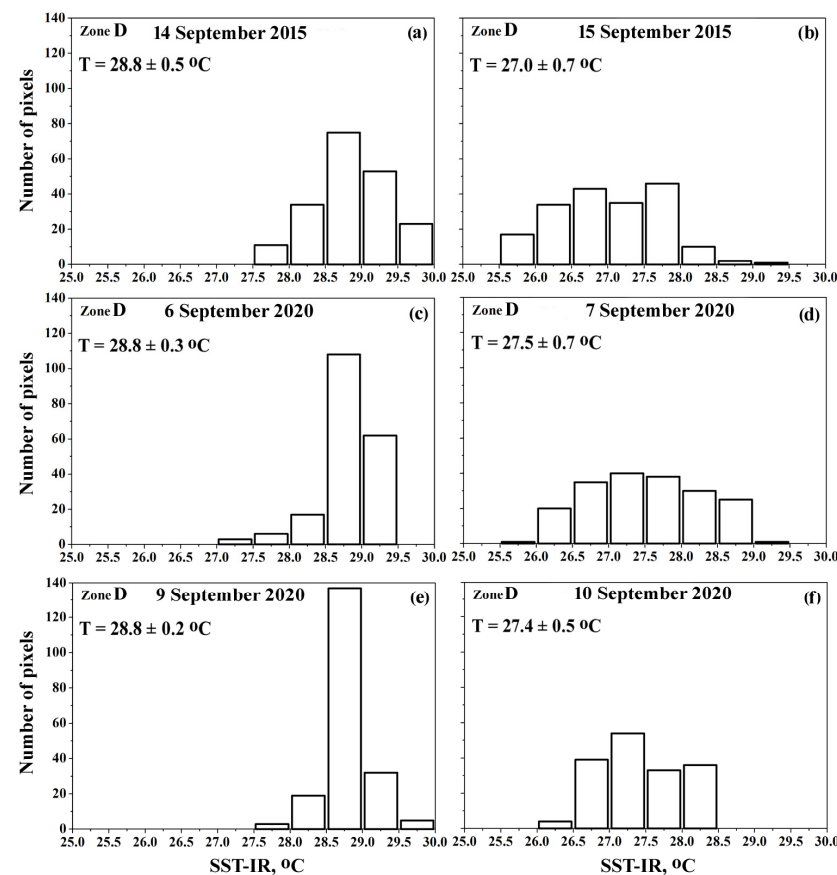


Figure 20. Statistical distribution of SST-IR based on all MODIS-Aqua pixels in zone D on the three couples of days: (a) 14 and (b) 15 September 2015; (c) 6 and (d) 7 September 2020; and (e) 9 and (f) 10 September 2020. T designates the average SST-IR ($\pm$ its standard deviation).

Our analysis showed the appearance of larger amounts of dust at high altitudes on the days of SST-IR drops (15 September 2015, 7 September 2020, and 10 September 2020) compared to lower amounts of dust at high altitudes on the days preceding SST-IR drops (14 September 2015, 6 September 2020, and 9 September 2020, respectively) (Figure 21). It should be noted that desert dust particles at high altitudes have a lower temperature than the sea surface temperature. Therefore, the appearance of larger amounts of dust at high altitudes on the days of SST-IR drops led to the shift in the SST-IR interval towards lower values in the flat distributions of SST-IR on those days (Figure 20). This shift caused the sharp drop in the average SST-IR on 15 September 2015, 7 September 2020, and 10 September 2020 to 27.0 ± 0.7 °C; 27.5 ± 0.7 °C; and 27.4 ± 0.5 °C, respectively (Figure 20). On those days of SST-IR drops, dust-related IR radiation, emitted by dust particles at high altitudes, essentially influenced SST-IR measurements by MODIS-Aqua IR radiometry. This was in comparison with the average SST-IR on the days preceding the SST-IR drops (14 September 2015, 6 September 2020, and 9 September 2020, respectively), when the average SST-IR was noticeably higher: 28.8 ± 0.5 °C; 28.8 ± 0.3 °C; and 28.8 ± 0.2 °C, respectively (Figure 20). It should be noted that the aforementioned SST-IR sharp drops on 15 September 2015, 7 September 2020, and 10 September 2020 did not reflect actual SST

as observed by SST-MW. These SST-IR sharp drops prevented the accurate detection of MHWs in the presence of weak dust intrusion.

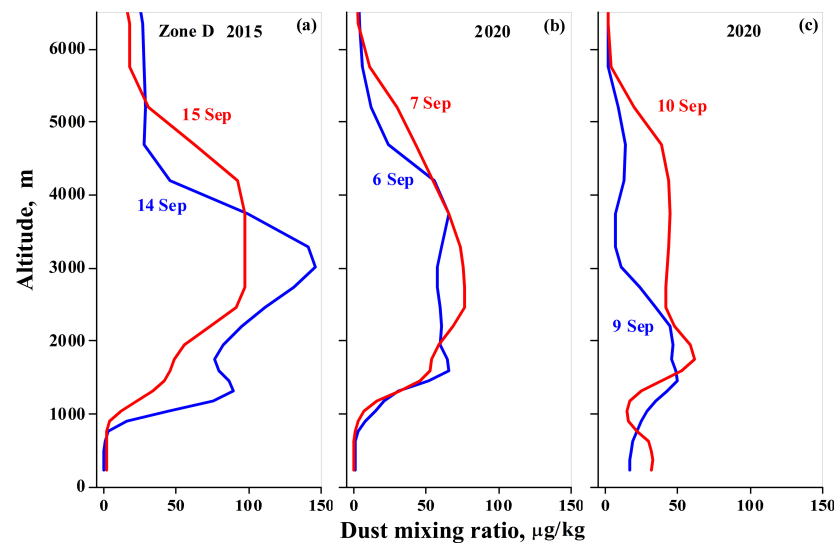


Figure 21. A comparison between the vertical profiles of MERRA dust mixing ratio on the days preceding the SST-IR drops and the vertical profiles of MERRA dust mixing ratio on the days of the SST-IR drops: (a) 14 and 15 September 2015; (b) 6 and 7 September 2020; and (c) 9 and 10 September 2020.

4. Discussion

Our analysis provides evidence that there was no effect of dust intrusion on the detection of MHWs by SST-MW. Using SST-MW, we detected MHWs in the following months: (1) September 2015, when a strong dust intrusion (AOD ranged within an extremely wide interval from 0.3 to 5) appeared over the EM (Table 1); (2) September 2020, in the presence of a weak dust intrusion, when AOD ranged from 0.3 to 0.4 (Table 2); and (3) September 2024, in the absence of a dust intrusion, when AOD was lower than 0.3 (Table 3). Even in the presence of a strong dust intrusion (7–16 September 2015), there was no relationship between the daily variations in SST-MW anomalies from its 90th PTH and the daily variations in AOD. Despite the significant variations in AOD during the strong dust intrusion, the SST-MW anomalies were positive, indicating the appearance of a MHW characterized by an abnormally high SST-MW (Figure 19a, the green line).

In contrast to SST-MW, in the presence of a strong dust intrusion (7–16 September 2015), SST-IR was incapable of detecting MHWs. We found an inverse correspondence between daily variations in SST-IR and daily variations in AOD. In particular, an increase in dust intrusion (6–8 September 2015, when AOD increased from 0.3 to 5), was accompanied by a decrease in SST-IR of up to 4 °C and a subsequent decrease in dust intrusion (8–16 September 2015 when AOD decreased from 5 to ~0.3) was accompanied by an increase in SST-IR. The obtained inverse correspondence between daily variations in SST-IR and daily variations in AOD indicates that, in the presence of a strong dust intrusion, SST-IR was profoundly influenced by desert dust causing erroneous daily variations in SST-IR. In turn, the erroneous daily variations in SST-IR prevented the detection of MHWs. The above-mentioned SST-IR failure to detect MHWs was in line with our previous studies on the effect of desert dust intrusion on the detection of lake heatwaves [27–29].

Not only did the above-mentioned erroneous daily variations in SST-IR retrievals prevent the detection of MHWs, but they also led to the formation of an incorrect spatial distribution of SST-IR in the EM. In particular, our analysis provides evidence that, in the presence of a strong dust intrusion (8–10 September 2015), the spatial distribution of the SST-IR values erroneously showed east–west gradients with warmer water to the western

part of the EM (Figure 6g–j). These gradients contradicted the actual east–west gradients with warmer water to the eastern part of the EM (zones B and D), as observed by SST-MW (Figure 6b–e).

An essential point of our study is that, even in the presence of a weak dust intrusion (in the first decade of September 2020, characterized by AOD ranging from 0.3 to 0.4), SST-IR was incapable of detecting MHWs. This SST-IR failure took place because daily variations in SST-IR revealed short-term sharp drops in SST-IR. These SST-IR sharp drops did not reflect the true behavior of actual SST, as observed by daily variations in SST-MW. Our analysis showed an increase in atmospheric dust at high altitudes on the days of SST-IR sharp drops compared to the amount of dust at high altitudes on the days preceding SST-IR drops (Figure 21). Note that the temperature of dust particles at high altitudes is lower than the sea surface temperature. Dust-related IR radiation, emitted by dust particles at high altitudes, could interfere with accurate measurement of SST by satellite IR radiometry, thereby causing erroneously low SST-IR retrievals. We consider that the appearance of higher amounts of dust at high altitudes caused the sharp drops in SST-IR on 15 September 2015, 7 September 2020, and 10 September 2020. This is in comparison with SST-IR on the days preceding the SST-IR drops (14 September 2015, 6 September 2020, and 9 September 2020, respectively). On those days, the amount of dust at high altitudes was lower and SST-IR was noticeably higher (Figures 20 and 21).

Previously we discussed difficulties with detecting MHWs in the presence of dust intrusion. Now we discuss our results in the absence of dust intrusion ($\text{AOD} < 0.3$). Our analysis showed that daily variations in both SST-IR and SST-MW were capable of similarly detecting MHWs in the absence of dust intrusion: from 17 to 30 September 2015 (Figures 8 and 9) and from 1 to 18 September 2024 (Figures 16 and 17). During these non-dusty periods, a small background amount of dust was still present in the atmosphere. Therefore, any occurrence of atmospheric instability encouraging upwelling airflow could increase dust amounts at high altitudes from time to time; thereby causing short-term sharp drops in SST-IR (Figure 17). However, these occasional sharp drops in SST-IR did not prevent the detection of MHWs.

The SST-IR dataset (representing MODIS_AQUA_L3_SST_THERMAL_DAILY_9KM_NIGHTTIME_V2019.0 product of SST) reprocessed nighttime SST using an algorithm corrected for dust effects at night [43]. Our findings highlight the following important point: the above-mentioned correction for dust effects was not effective. This was because SST-IR failed to detect MHWs in the presence of dust intrusion. As discussed by Luo et al. [32], the above-mentioned SST-IR's failure took place because the correction did not take into account explicit dependences on dust altitude and dust concentration.

Finally, we assessed the ability to detect MHWs by the SST-MUR dataset (representing the Multiscale Ultrahigh Resolution Global Foundation SST analysis). This dataset integrates SST data from satellite MW and IR radiometry. Our analysis provides evidence that, in the presence of strong dust intrusion (7–16 September 2015), SST-MUR was not capable of detecting MHWs (Figure 10). We consider that the SST-MUR's failure resulted from the optimal interpolation of both correct SST-MW data and erroneous SST-IR data in the presence of strong dust intrusion. In particular, the erroneous SST-IR contributed to the observed inverse correspondence between daily variations in SST-MUR and daily variations in AOD (Figure 10). An increase in AOD of 0.3 to 5 from 6 to 8 September 2015 was accompanied erroneously by a decrease in SST-MUR of up to 3 °C (Figure 10). This was followed by a decrease in AOD from 5 to 0.3, which was erroneously accompanied by an increase in SST-MUR (Figure 10). This is evidence that daily variations in SST-MUR were profoundly influenced by atmospheric dust. The erroneous daily variations in SST-MUR prevented the detection of MHWs in the presence of strong dust intrusion. Moreover, similarly to

SST-IR, from 8 to 10 September 2015, the SST-MUR spatial distribution showed erroneous east–west gradients indicating warmer water to the western part of the EM (Figure 6m–o). These east–west gradients contradicted the actual east–west gradients indicating warmer water to the eastern part of the EM, as observed by SST-MW (Figure 6c–e).

The failure of SST-MUR to detect MHWs was also observed in the presence of weak dust intrusion. For example, in the first decade of September 2020, SST-MUR started showing MHWs four days later than SST-MW did (Table 2). Therefore, our findings highlight the following important point: in the presence of desert dust intrusion, the incapability of SST-IR to detect MHWs substantially reduced the capability of SST-MUR to detect MHWs.

It is reasonable to suggest that our results are true not only for the Multiscale Ultra-high Resolution Global Foundation SST analysis (SST-MUR), but also for other integrated SST datasets, such as the products developed by the Copernicus Marine Environment Monitoring Service (CMEMS) [53] and by NOAA (OISST V2.1) [54]. In the presence of dust intrusion, the aforementioned datasets (integrating satellite MW and IR radiometry of SST) could underestimate the occurrence of MHWs. As a result, the previous studies of MHWs, which were based on the CMEMS and NOAA OISST V2.1 datasets, may not have included MHWs observed in the presence of dust intrusion [13,15]. This could lead to an underestimation of the presence of MHWs, as an essential indicator of regional warming in the Eastern Mediterranean Sea.

Below we discuss the following three specific features of our approach:

(1) Hobday et al. [17] defined MHWs as prolonged periods of abnormally high SST, allowing interruptions of up to 2 days. Note that their approach to define the duration of MHWs involves using actual SST. However, in this study, we chose to allow a one-day interruption in the presence of dust intrusion. The reason was to find out if this interruption was caused by actual SST changes or by dust-induced artifacts. Our analysis provides observational evidence that, in the presence of desert dust intrusion, SST-IR was profoundly influenced by atmospheric dust. The dust appearance at high altitudes interfered with the accurate detection of MHWs, contributing to the formation of SST-IR sharp drops. These SST-IR sharp drops did not reflect the behavior of actual SST, that is, they were dust-induced artifacts. For dust-induced artifacts, it does not matter how many interruptions we use: one day or more. Given the above information, our findings highlight the importance of analyzing physical factors responsible for interruptions of MHWs—namely, whether these interruptions are actual SST changes or dust-induced artifacts.

(2) The time frame of this study is limited by the 23-year period of availability of the SST-IR and SST-MUR datasets (Section 2.2). In accordance with Hobday et al. [17], the standard climatological period for MHW detection is typically 30 years. Recently, Schlegel et al. [55] found that MHWs detected in a time series as short as 10 years did not have a duration or intensity appreciably different from events detected in a standard 30-year long timeseries. Based on their results, one can suggest that the duration or intensity of the MHWs, detected in this study using a 23-year long timeseries, differ very little (if at all) from the duration or intensity of the MHWs detected in a standard 30-year timeseries. It is also worth noting that our findings relate to specific desert dust intrusions, which are not connected to any climatological periods.

(3) Our analysis showed that the difference between the MHWs detected by SST-MW (taken at daily minimum SST) and the MHWs detected by SST-IR (taken at a fixed time of 01:30 LT) was mainly determined by the influence of desert dust intrusion, whereas the time difference of the SST observations was much less essential. We found that, in the presence of strong dust intrusion (7–16 September 2015), SST-IR failed to detect MHWs while SST-MW succeeded (Figures 8 and 9). Whereas, in the absence of dust intrusion

(1–18 September 2024), both the SST-MW and SST-IR datasets succeeded in showing similarities in the occurrence of MHWs (Figures 16 and 17). One can see that the time difference of the SST observations was of little relevance. Therefore, this time difference between SST-MW and SST-IR cannot alter our main conclusions about the incapability of SST-IR to detect MHWs in the presence of desert dust intrusion.

5. Conclusions

In this study, the effect of desert dust intrusion on the detection of MHWs in the EM has been investigated by separate use of MW and IR satellite radiometry of nighttime SST. We focused on the months of September during the study period (2002–2024) when dust intrusions from both the Middle East sources and the Sahara Desert can be observed over the Eastern Mediterranean.

For the first time, our analysis provides observational evidence that there was no effect of desert dust intrusion on the detection of MHWs by SST-MW, when AOD ranged within an extremely wide interval from 0.3 to 5. All four specified zones (A, B, C, and D) experienced MHWs. This illustrates the large scale of this phenomenon in the EM.

In contrast to SST-MW, in the presence of a strong dust intrusion (7–16 September 2015), SST-IR was incapable of detecting MHWs. We found an inverse correspondence between daily variations in SST-IR and daily variations in AOD. In particular, an increase in dust intrusion (6–8 September 2015, when AOD increased from 0.3 to 5) was accompanied by a decrease in SST-IR of up to 4 °C and a subsequent decrease in dust intrusion (8–16 September 2015, when AOD decreased from 5 to 0.3) was accompanied by an increase in SST-IR. The obtained inverse correspondence between daily variations in SST-IR and daily variations in AOD indicates that, in the presence of strong dust intrusion, SST-IR was profoundly influenced by desert dust, causing erroneous daily variations in SST-IR. In turn, these erroneous daily variations in SST-IR prevented the detection of MHWs. An essential point of our study is that, even in the presence of weak dust intrusion, SST-IR was incapable of detecting MHWs due to the occurrence of erroneous short-term sharp drops in SST-IR. This was because of dust appearance at high altitudes. Our findings highlight the importance of analyzing physical factors responsible for MHW interruptions—namely, whether these interruptions are actual SST changes or dust-induced artifacts.

Note that the SST-IR dataset (representing the MODIS_AQUA_L3_SST_THERMAL_DAILY_9KM_NIGHTTIME_V2019.0 product of SST) reprocessed nighttime SST data using an algorithm corrected for dust effects at night [43]. Our findings showed that the above-mentioned correction for dust effects was not effective: in the presence of dust intrusion SST-IR failed to detect MHWs. This failure took place because the correction did not take into account explicit dependences on dust altitude and dust concentration [32].

We assessed the ability of detecting MHWs by SST-MUR (representing the Multiscale Ultrahigh Resolution Global Foundation SST analysis), which integrated SST data from satellite MW and IR radiometry. Our analysis provides evidence that, in the presence of desert dust intrusion, the incapability of satellite IR radiometry to detect MHWs substantially reduced the capability of SST-MUR to detect MHWs. This leads to an underestimation of the presence of MHWs, which is an essential indicator of regional warming in the EM, thereby highlighting the practical significance of our results.

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Abbreviations

AOD	aerosol optical depth
EM	Eastern Mediterranean
MHW	marine heatwave
LT	local time
IR	infrared radiation
MW	microwave radiation
MUR	multiscale ultrahigh resolution
SST	sea surface temperature
SST-MW	SST based on MW radiometry
SST-IR	SST based on IR radiometry
SST-MUR	MUR SST analysis
SISR	METEOSAT-based surface incoming solar radiation
90th PTH	ninetieth percentile threshold
MI	maximal intensity of MHWs
CI	cumulative intensity of MHWs

Appendix A

Variations in solar radiation over the study area in the EM in September 2015.

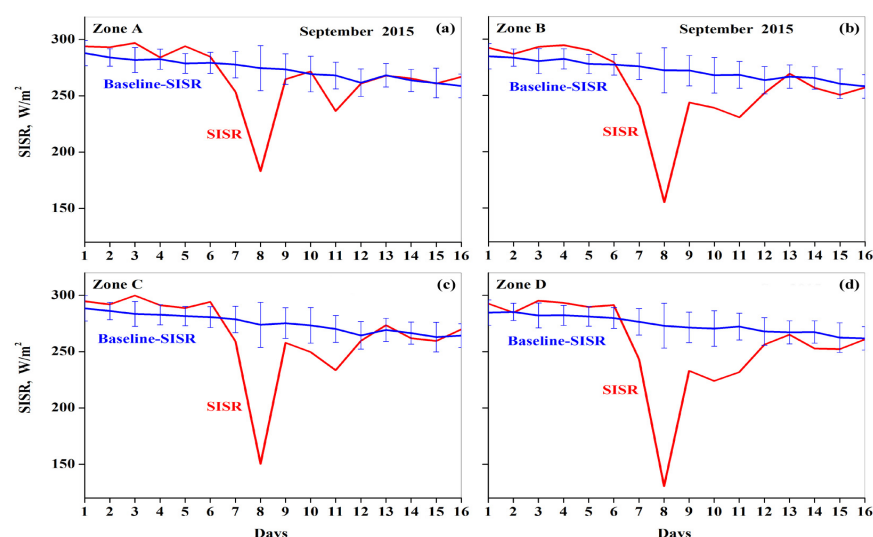


Figure A1. Day-to-day variations in METEOSAT-based daily averaged surface incoming solar radiation (SISR) over the specified zones: (a) A, (b) B, (c) C, and (d) D, from 1 to 16 September 2015. The blue lines designate the baseline SISR, which was defined as the average SISR over the September months during the baseline period (2002–2024). The standard deviation of baseline SISR is designated by short vertical lines.

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