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The 2025 Mediterranean marine heatwave in the context of climate change through sea surface temperature analogues

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a supprimé: Correspondence: Davide Faranda (davide.faranda@cea.fr)

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a supprimé: The Mediterranean Sea experienced a record breaking marine heatwave in 2025, raising questions about the influence of human-induced climate change. Using an analogue-based attribution approach, we compared historical sea surface temperature (SST) patterns from ERA5 reanalysis (1950–2024) to those observed during the event. By identifying the most similar SST anomaly patterns in a past period (1950–1986) and more recent one (1987–2024), we assessed changes in SST and related atmospheric variables. We find that, under present-day climate conditions, analogous patterns result in significantly higher SST anomalies and stronger atmospheric responses—such as warmer near-surface temperatures and intensified radiative fluxes—compared to the past. Statistical tests confirm that long-term warming trend has amplified Mediterranean SST extremes by up to 1.5°C and associated heat exchange processes, though shifts in large-scale natural climate variability may also influence these outcomes, complicating attribution. Nonetheless, the dominant contribution to the 2025 marine heatwave severity is attributable to anthropogenic (... [1])

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a supprimé: which is amplified by the influence of anthropogenic global warming,

a supprimé: 2025).

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Abstract

The Mediterranean Sea experienced an exceptional marine heatwave in early summer 2025 lasting from 20 to 30 June. Here we analyse this event using an analogue framework that differs from the more common circulation based analogue attribution approach. Instead of identifying atmospheric circulation analogues first, we search directly for historical analogues of the observed sea surface temperature (SST) anomaly pattern and then compare the associated atmospheric and surface conditions in a past period (1950 to 1986) and a present one (1987 to 2024), based on ERA5 daily fields over the Mediterranean during June to September. Our results suggest that the present period exhibits higher SST anomalies than the past one, with the strongest positive differences over the western Mediterranean and the Adriatic. Warmer 2 m air temperatures over surrounding land areas and higher incoming shortwave radiation over broad parts of the basin are also observed, while sea level pressure, wind speed, latent heat flux, sensible heat flux, and longwave radiation display smaller and more spatially heterogeneous changes. Thus, the 2025 event occurred in a warmer thermodynamic background than analogous SST patterns in earlier decades. They do not constitute a complete form of attribution on their own, since the framework cannot fully separate externally forced trends from internal variability and does not explicitly resolve ocean dynamical processes such as advection, mixing, and stratification changes. Nevertheless, the analogue analysis supports the interpretation that long term warming contributed substantially to the intensity of the 2025 Mediterranean marine heatwave and shows how SST analogue comparisons can complement existing attribution approaches for marine extremes.

1. Introduction

Anthropogenic climate change has unequivocally warmed the oceans and the atmosphere, increasing the frequency and intensity of different extreme events (Forster et al., 2025; Seneviratne et al., 2021). Among them, marine heatwaves (MHWs) are prolonged periods of unusually warm ocean temperatures and represent one of the clearest manifestations of the interaction between climate internal variability and long-term change in the ocean (Hobday et al., 2016; Holbrook et al., 2020). Their frequency, duration, and intensity have increased over the last century, at the global scale (Frölicher et al., 2018; Oliver et al., 2018; Laufkötter et al., 2020), as evidenced by the recent surge in both global and regional extreme heat events (Gyuleva et al., 2022; England et al., 2025, Guinaldo et al., 2025). These events can produce severe ecological and socioeconomic impacts, including mass mortality of marine organisms, coral bleaching, seagrass decline, and fishery disruption (Smale et al., 2019; Smith et al., 2021; Garrabou et al., 2022; Wernberg et al., 2025).

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The Mediterranean Sea is a particularly sensitive region in this context. It is widely recognized as a climate change hotspot (Giorgi 2006), with regional warming trend exceeding the global average (Cramer et al., 2018; Tuel & Eltahir, 2020; Pastor et al., 2020; Seneviratne et al., 2021). Consistent with this background trend, Mediterranean MHWs have become more frequent, longer, and more intense in recent decades (Darmar et al., 2024) with an annual mean number of days increasing from 1 day/year over the period 1982-1999 to 5.5 days/year over the period 2000-2021 (Pastor & Khodayar, 2023). Several remarkable events have been documented during the last two decades (Simon et al., 2023; Guinaldo et al., 2023; Martínez et al., 2020; Pastor et al., 2024) with major impacts on marine ecosystems and coastal environments (Coll et al., 2020; Garrabou et al., 2022; Artana et al., 2026). Recent work has also highlighted that Mediterranean MHWs can be intensified when they co-occur with atmospheric heat extremes and anomalous summer circulation patterns that favour enhanced radiative input and weak surface winds (Sen Gupta et al., 2020; Pastor et al., 2024; Bonino et al., 2025; Paredes-Fortuny et al., 2025) conditions whose frequency is itself increasing (d'Andrea et al. 2024).

The contribution of anthropogenic climate change to the increasing likelihood and intensity of MHWs is not unequivocally established, with the vast majority of observed events attributable to human influence (Frölicher et al. 2018). The question addressed here is more specific. We examine the June 2025 Mediterranean event using an analogue framework designed to compare physically similar SST anomaly patterns across different climate backgrounds. The aim is not to replace formal probabilistic attribution studies based on climate model ensembles, but to provide an event-specific observational line of evidence and a process-oriented diagnosis of how the background thermodynamic environment differs between earlier and more recent analogues.

Analogue-based attribution has become an established complementary approach in extreme event attribution (Vautard et al., 2016; Faranda et al., 2022; Faranda et al., 2024). In its more classical form, the method first identifies atmospheric circulation analogues and then evaluates how associated impacts differ between climate states. Here we adopt a different perspective. We first identify analogues of the observed SST anomaly pattern itself, and only then examine the atmospheric and surface fields associated with those SST analogue dates. This choice is motivated by the nature of the event under study, namely a MHW, for which the SST pattern is the central feature to be matched.

The study has three objectives. First, we document the exceptional character of the June 2025 event (Section 3). Second, we assess how the associated SST, atmospheric, and air-sea flux anomaly composites differ between past and present SST analogues (Section 4). Third, we discuss the extent to which these differences are consistent with thermodynamic amplification in a warmer climate, while explicitly acknowledging the limits of the analogue framework, in particular its inability to isolate forced and internal components fully and its omission of explicit ocean dynamical processes (Section 5).

2. Data and Methods

2.1 Reanalysis and observational datasets

The main dataset used in this study is the ECMWF ERA5 reanalysis (Hersbach et al., 2020). ERA5 provides globally gridded atmospheric and surface fields at 0.25° resolution from 1940 onward. In this work, ERA5 is used as a temporally consistent, observation constrained dataset for both the characterization of the 2025 event and the identification of historical analogues. All analyses are restricted to the June to September season (JJAS).

a supprimé: These extreme ocean warming events can have devastating ecological and socio-economic impacts (Smith et al., 2021; Wernberg et al., 2025). MHWs trigger mass mortality of marine organisms, coral bleaching, seagrass die-offs, and fisheries disruptions (Smale et al., 2019; Garrabou et al., 2022). Biodiversity hotspots are particularly vulnerable, as many species already live near their thermal tolerance limits (Smale et al., 2019). Given the severity of these impacts, effectively attributing marine heatwaves to anthropogenic climate change is essential for understanding their increasing frequency and for developing informed, forward-looking adaptation and mitigation strategies.¶

The Mediterranean Sea, as a climate change "hotspot", is a region of special concern for climate extremes (Cramer et al., 2018; Tuel et al., 2020). Regional warming has outpaced the global average in recent decades (Pastor et al., 2020), and this trend is projected to continue with mean and summer temperatures rising faster than the global ones (Adloff et al., 2015; Lionello & Scarascia, 2018; Seneviratne et al., 2021). Consistent with these trends, the Mediterranean has experienced an increase in the frequency, intensity and duration of MHWs (Pastor & Khodayar, 2023) and a series of record-breaking marine heatwaves in the past two decades (Martínez et al., 2023) notably during the summers of 2003, 2012, 2017, 2018, and 2022 causing widespread ecosystem impacts (Estaque et al., 2023; Garrabou et al., 2022). The summer 2022 Mediterranean MHW was, until recently, one of the most intense on data records, with large areas of the western Mediterranean Sea exceeding +5 °C anomalies (Guinaldo et al., ...

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For SST, the ERA5 product relies on observationally constrained analyses rather than on a fully coupled ocean reanalysis. In practice, the SST field combines HadISST for the earlier part (before 2007) of the record and OSTIA in the more recent period (after 2007), both regridded within the ERA5 framework. We therefore refer to ERA5 SST as a consistent gridded SST product used within ERA5, rather than as an ocean reanalysis field in the strict dynamical sense.

The variables analysed in the analogue-based attribution are SST, 2 m air temperature (T2m), mean sea level pressure (MSL), surface net shortwave radiation (SSR), surface net longwave radiation (STR), surface latent heat flux (SLHF), surface sensible heat flux (SSHF), and 10 m wind speed (WSPD, derived from U10 and V10). These variables were selected because they are relevant to the development and maintenance of summer MHWs in the Mediterranean Sea through radiative forcing, air-sea exchanges, and near surface circulation (Capotondi et al., 2024; Damaraki et al., 2024, Bonino et al. 2025).

For descriptive purposes in the event characterization section, we also use the Mediterranean Sea High Resolution L4 Sea Surface Temperature Reprocessed product (MED REP L4; Copernicus Marine Service Information, <https://doi.org/10.48670/moi-00173>). This observational product is not used in the analogue protocol and its role is only to document the timing, spatial structure, and magnitude of the 2025 event with an independent observational perspective.

2.2 Definition of anomalies and target event

For ERA5, daily anomalies are computed at each grid point relative to the 1950 to 2024 JJAS daily climatology. Thus, for each calendar day, the corresponding climatological mean for that day is removed before further analysis. All variables are then smoothed with an 11 day centred moving average, following the Climameter framework and ensuring that the target event and candidate analogue fields are compared at the same temporal scale (Faranda et al., 2024). The target event is defined as the temporal mean SST anomaly over 20 to 30 June 2025. Daily SST anomalies are first computed, then averaged over this 11 day period. This period was selected because it corresponds to the most rapid build up and peak phase of the exceptional western Mediterranean warming documented by the observational datasets and by ERA5. The target is therefore a temporally averaged SST anomaly field, not a single day snapshot.

2.3 Analogue selection

We search for analogues of the 20 to 30 June 2025 SST anomaly pattern over the Mediterranean basin. The matching domain is the entire Mediterranean basin and immediate coastal grid points represented in ERA5. For each JJAS day in the historical record, we compute the Euclidean distance between the candidate daily SST anomaly field and the target event pattern. The distance is calculated over all grid points in the domain, with cosine of latitude weighting to account for the different area represented by each grid cell. Candidate days are then ranked from the smallest to the largest distance. The analogue days are those with the smallest distances (i.e., the first 1% of dates), that is, the SST anomaly fields most similar to the target 2025 pattern. The search is performed independently for two subperiods, a past period, 1950 to 1986, and a present period, 1987 to 2024. The year 1987 is used as the split because it lies close to a documented acceleration in Mediterranean warming and also divides the record into two comparably sized samples (Lionello & Scarascia, 2018). We stress that the past period is not a pre industrial baseline. It is simply a cooler segment of the observational era, that could be cooler due to the decrease in aerosol emissions over western Europe or a different phase of the multidecadal variability (Pisano et al. 2020).

In each period we retain the top 42 analogue days. This corresponds to about 1% of all available JJAS days in each subperiod and follows the standard Climameter choice adopted in previous sensitivity analyses

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(Faranda et al., 2024). Fixing the number of analogues in both periods allows direct comparison of composite means between the two climate backgrounds.

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For each period, we compute composites by averaging the selected analogue days for SST, T2m, MSL, SST, SLHF, SSHF, and WSPD. We then compare the past and present composites as well as the present minus past difference. This difference is interpreted as a diagnostic of how the environmental conditions associated with similar SST anomaly patterns differ between the earlier and later parts of the record. A positive difference indicates that the present climate analogues are associated with stronger positive anomalies consistent with a warming signal. For instance, a positive SST difference implies that recent analogues occur under warmer SST conditions than similar events in the past. Conversely, near-zero or negative differences suggest either no significant change or a reduction in anomaly amplitude under current climate conditions, though this is less common for variables associated with heat extremes. We remark that this framework does not justify a claim that identical atmospheric or oceanic states are being compared. It compares atmospheric and surface conditions associated with similar SST anomaly patterns. The method is therefore best understood as conditional and diagnostic. It provides information on how the thermodynamic and near surface atmospheric context of SST analogue events has shifted between the two periods, but it does not in itself isolate external forcing from internal variability.

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2.4 Statistical significance

To assess whether present minus past composite differences are robust to sampling uncertainty, we use a non-parametric bootstrap test following Faranda et al. (2022, 2024). The 84 analogue dates, 42 from the past and 42 from the present, are pooled together. We then generate 10,000 random resamples, each time dividing the 84 dates into two groups of 42 without preserving their original period labels. For each resample, we compute the difference between the two composite means at each grid point. The resulting empirical distribution provides the expected range of differences under the null hypothesis that the observed present minus past difference arises from random sampling within the pooled analogue set. Grid point differences are considered significant at the 95% level when they fall outside the 2.5th to 97.5th percentile interval of the bootstrap distribution. A false discovery rate correction is applied to account for multiple testing across the spatial domain (Wilks, 2016).

2.5 Climate variability indices and analogue quality

To characterize the background large scale variability associated with the analogue dates, we analyse standard climate indices, El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), East Atlantic pattern (EA), and Scandinavian pattern (SCAND). For each analogue date we extract the value of the corresponding index time series and compare the past and present distributions using violin plots and a two tailed Cramér von Mises test. These comparisons are purely descriptive and inform on the large-scale context without demonstrating a causal role of any given mode in the 2025 event. We also evaluate analogue quality using the mean Euclidean distance between the target 2025 SST pattern and its selected analogues, following Faranda et al. (2022). This quality metric indicates how closely the selected analogue set matches the target pattern relative to typical analogue distances within each period.

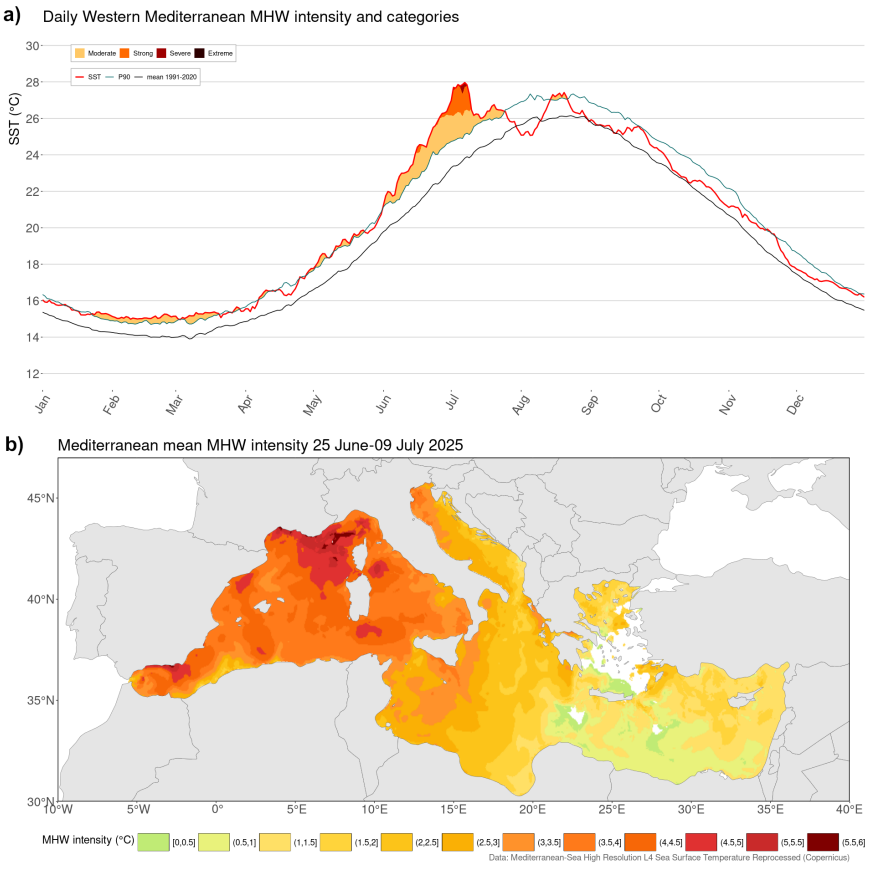
3. The June 2025 Mediterranean marine heatwave

The June to July 2025 MHW was exceptional in both duration and spatial extent. Figure 1a shows the daily mean western Mediterranean SST together with the 1991 to 2020 mean climatology, the 90th percentile threshold used to define MHW conditions and the MHW category (Hobday et al. 2016, Hobday et al. 2018).

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455 The event developed progressively during June 2025, with SST remaining above the climatological threshold
456 for the whole month and then intensifying sharply in the second half of June and the start of July. According
457 to this, western Mediterranean presented moderate MHW conditions persisting from early June to late July,
458 with two periods of stronger intensity. A short strong phase occurred in mid June, followed by a more sustained
459 severe phase around the turn of June to July. The daily western Mediterranean SST reached its maximum
460 close to 28 °C in early July. MHW intensity rapidly decayed until its end in mid-July. This time evolution of the
461 MHW event classifies it as a long-duration event, significantly exceeding the average of 16 days for
462 Mediterranean MHWs in the period 1982–2021 (Pastor et al., 2023).

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464 **Figure 1.** a) Annual mean daily SST averaged over the Western Mediterranean Sea and MHW category
465 (shaded areas) for 2025 and b) mean MHW intensity for 25 June-09 July 2025 period (strong category in
466 panel a). SST data obtained from the Mediterranean Sea-High Resolution L4 Sea Surface Temperature
467 Reprocessed (MED-REP-L4) dataset from Copernicus.

468 Figure 1b shows the mean MHW intensity over the Mediterranean Sea for the period 25 June to 09 July 2025,
469 corresponding to the peak phase identified in Figure 1a. The strongest intensities were concentrated in the

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western Mediterranean, particularly between the Gulf of Lions, the Balearic Sea, Corsica, Sardinia, and the Tyrrhenian sub-basin, with local values above +4.5 °C and in some areas approaching +5.5 to 6 °C. Positive intensities extended across most of the basin, but with a clear west to east decrease. The central Mediterranean showed widespread moderate to strong conditions, whereas the eastern Mediterranean exhibited weaker intensities overall. The spatial MHW intensity distribution qualifies it as a western Mediterranean-centred event (Fig 1b), which motivates the following sections to be focused on this basin. The event affected much of the Mediterranean, but its most exceptional expression was clearly located in the western basin. The temporal window 20 to 30 June 2025 used for the analogue target therefore corresponds to the onset of the strongest basin-wide phase and captures the spatial structure that later culminated during the 25 June to 09 July interval shown in Figure 1b.

ERA5 shows that the event coincided with positive MSL anomalies over parts of southwestern and central Europe (Fig. 2i) and with widespread positive SSR anomalies over the Mediterranean region (Fig. 2m). T2m anomalies were strongly positive over surrounding land areas, especially over the Iberian Peninsula, southern France, Italy, and North Africa (Fig. 2e). WSPD anomalies were weak to moderate and spatially heterogeneous (Fig. 2ac). These features are consistent with a hot and radiatively favourable large scale environment during the peak phase of the event, but the present paper does not attempt a formal classification of the associated atmospheric circulation pattern or of concurrent atmospheric heatwaves.

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4. Results

4.1 SST analogue composites

Figure 2a–d compares the target SST anomaly field for 20 to 30 June 2025 with the past and present SST analogue composites and with their difference. The past and present composites both reproduce the broad spatial structure of the target event, with stronger anomalies in the western Mediterranean than in the eastern basin. This indicates that the 2025 pattern is not unprecedented in terms of its large-scale spatial organization. The amplitudes, however, differ between the two analogue periods. The past composite shows weaker positive SST anomalies than the present composite over much of the basin. The present minus past SST difference is positive over large areas, with the strongest values in the western Mediterranean and parts of the Adriatic. Many of these positive differences are significant at the 95% level after bootstrap testing. Within the analogue framework, similar SST anomaly patterns are associated with systematically higher SST anomalies in the later part of the record.

a supprimé: We then compare the actual observed composite difference (present minus Past) to this bootstrap distribution at each grid point. Statistical significance at the 95% confidence level is determined by whether the observed difference lies outside the central 95% range of the bootstrap distribution (two-tailed). In practice, we identify grid points where the observed difference exceeds the 97.5th percentile or falls below the 2.5th percentile of the bootstrap distribution, flagging those as significant increases or decreases, respectively. The resulting significance mask highlights regions where the difference between present and past composites is robust to sampling uncertainty. Given the large number of spatial grid points, we apply a false discovery rate (FDR) correction to control for field significance (Wilks, 2016). In our case, the spatial coherence of the patterns—broad regions showing consistent changes—adds confidence to the robustness of the detected signals. By combining deterministic analogue-based composites with a statistical significance framework, our methodology provides both a physically grounded and statistically robust assessment of how the characteristics of the 2025 Mediterranean SST extreme would likely have differed under a cooler historic climate

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4.2 Near surface air temperature and pressure

Figure 2e–h shows the T2m fields. The target event exhibits strong positive air temperature anomalies over land surrounding the Mediterranean. Both past and present analogue composites retain positive T2m anomalies over southern Europe and North Africa, but the present composite is generally warmer. The present minus past T2m difference is positive over substantial land areas, with significant values over parts of the Iberian Peninsula, southern France, Italy, the Balkans, and North Africa. Over the sea, T2m differences are smaller and less spatially coherent. The target event is associated with positive pressure anomalies over the western and central Mediterranean sector and negative anomalies farther east. The past and present analogue composites show broadly similar large scale pressure structures. In contrast to SST and T2m, the present minus past MSL differences are weaker, spatially heterogeneous, and often not significant over the basin. This suggests that the pressure patterns associated with the SST analogues do not differ as strongly between the two periods as the thermodynamic fields do.

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4.3 Radiative fluxes

Figure 2m–p shows SSR. During the target event, positive shortwave anomalies cover much of the Mediterranean and adjacent land areas. Both analogue composites also display positive SSR anomalies, but the present composite is generally stronger over broad parts of the basin and neighbouring regions. The present minus past SSR differences are positive over much of the western and central Mediterranean and are significant at many grid points. Figure 2q–t shows STR. The target event presents negative STR anomalies over wide marine areas, while the analogue composites are weaker and more spatially mixed. The present minus past STR difference is not uniformly positive over the basin. Instead, it shows a heterogeneous structure, with positive values in some areas and near zero or negative values elsewhere. The signal is therefore less spatially robust than for SST, T2m, or SSR, and its interpretation requires caution.

4.4 Turbulent heat fluxes and wind speed

Figure 2u–x shows SLHF. The event field and the analogue composites display mixed spatial structures. The present minus past difference is generally weak and heterogeneous, with localized positive and negative regions and limited significance. Within this framework, SLHF does not show a basin wide shift comparable to that seen in SST or SSR. Figure 2y–ab shows SSHF. Here again the present minus past differences are modest and spatially variable. Over parts of the Mediterranean basin the differences are close to zero, while surrounding land and coastal regions show a mix of positive and negative values. The SSHF response is therefore not spatially coherent at the basin scale. Figure 2ac–af shows WSPD. The target event is associated with generally weak wind anomalies over much of the basin, but with pronounced regional contrasts. The past and present composites also show weak and heterogeneous wind anomaly structures. Present minus past wind speed differences are small in most regions and only locally significant.

4.5 Climate variability indices and analogue quality

The distributions of ENSO (El Niño–Southern Oscillation), NAO (North Atlantic Oscillation), PDO (Pacific Decadal Oscillation), AMO (Atlantic Multidecadal Oscillation), EA (East Atlantic pattern), and SCAND (Scandinavian pattern) differ between past and present analogue dates according to the two-tailed Cramér–von Mises test, with $p < 0.001$ for all six indices (Figure 3). Because the sample is limited to 42 dates per period, these p-values quantify a clear distributional shift but should not be over-interpreted as a precise probability statement. The indices are taken from the following sources: ENSO 3.4 from ERSSTv5 (Extended Reconstructed Sea Surface Temperature version 5); PDO from SWFSC (Southwest Fisheries Science Center); NAO from ICPC (International Climate Prediction Center); AMO from ERSST TS (Extended Reconstructed Sea Surface Temperature time series); EA and SCAND from CPC (Climate Prediction Center, NOAA). The Figure 3 shows consistent shifts between past and present distributions for all modes. ENSO moves from a distribution centred on negative values in the past to values closer to neutral or slightly positive in the present, with a reduced spread. NAO shifts from a predominantly positive distribution in the past to a distribution centred on negative values in the present, with a broader range. PDO changes from a distribution centred on positive values to one centred on negative values. AMO shifts from weakly negative values toward values closer to zero or slightly positive. EA changes from a past distribution with two preferred states, one negative and one positive, to a present distribution concentrated near neutral values. SCAND shifts from positive values in the past to negative values in the present. These differences indicate that the analogue dates in the two periods sample different large-scale states of oceanic and atmospheric variability. The result is statistical and does not imply that any of these modes individually explains or causes the 2025 event but they might have contributed to the occurrence of the event. Finally, the analogue quality analysis (Figure 4) shows that the selected analogue sets reproduce the target circulation pattern with comparable skill in both periods.

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The 2025 event lies within the range of analogue quality values but toward the upper part of the distributions. This indicates that the event is not outside the analogue space but is not among the most typical configurations. The comparison between periods does not show a systematic improvement of analogue quality in the present climate, despite the temporal proximity of the event.

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a supprimé: The June 2025 Mediterranean Marine Heatwave: An exceptional event
The summer 2025 MHW in the Mediterranean was extreme in both intensity and spatial extent. Daily mean SST anomalies averaged over the Western Mediterranean have been investigated from two different SST datasets. Daily averaged SST anomalies are shown in Fig. 1 for NCEI (fig. 1a) and OSTIA (fig. 1b) for the 1982-2025 period (relative to the 1991-2020 baseline). In both analyses, SST anomaly sharply increased in June toward its maximum value by late June, clearly surpassing previous years and any previous historical records. For the NCEI case, the maximum anomaly exceeded +4 °C in the first days of July (exceeding by +0.5 °C the July 2023 record) while the OSTIA maximum anomaly reached +3.4 °C, surpassing the +2.9 °C July 2023 value. This suggests that the second half of June and early July clearly outstand all previous records, although SST summer anomalies lied outside the average variability during the previous years, except for June 2024. Both datasets exhibit a new SST monthly record for June. Thus the nature of June 2025 is exceptional not only to the long term past but also to the warmer summers of 2022-2024. A noteworthy aspect is that, the month of June and the beginning of July 2025 stand out significantly as an event of extraordinary anomalous SST warming, even in the context of recent warming. ^[1]
Spatially, the peak of the heatwave (late June–early July 2025) covered virtually the entire Mediterranean Sea. On 30 June 2025, positive SST anomalies exceeded +4 °C in the western Mediterranean (particularly the Gulf of Lion and Balearic Sea), and +2 to +3 °C anomalies were common elsewhere (Fig. 2a). The pattern featured a west east gradient with the western basin. This pattern suggests a strong MHW in the western Mediterranean, consistent with previous MHWs such as June 2003 and 2022 embedded in a basin-wide warming. The spatial structure of SST anomalies is important as it influences atmosphere feedback; for instance, intense warming of the western Mediterranean can drive regional atmospheric high-pressure anomalies (Drobinski et al., 2018). ^[1]
The heatwave coincided with a persistent atmospheric high-pressure system over the western Mediterranean region (Paredes-Fortuny et al., 2025). On 30 June 2025, ERA5 reanalysis shows an anomalous anticyclone centered over south-central Europe and the western Mediterranean, with MSLP about +5 hPa above normal over Spain, France, and the western Mediterranean, and compensating trough (slightly below-normal pressure) over the eastern Mediterranean (Fig. 2i). This synoptic ... [13]

a supprimé: The concurrence of a marine and atmospheric heatwave in 2025 aligns with recent findings that co-occurring hot atmospheric conditions can amplify MHW intensity (Pastor et al., 2024). In essence, the atmosphere and ocean acted in tandem: a stable, hot atmosphere suppressed surface winds and cloud formation, maximizing solar heating of an already warmer-than-average sea surface. ^[1]

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Figure 2. Multi-variable analogue analysis for the period 20-30 June 2025. Rows: sea-surface temperature, SST (a–d); 2-m air temperature, T2m (e–h); mean sea-level pressure, MSL (i–l); surface net shortwave

radiation, SSR (m–p); surface net longwave radiation, STR (q–t); surface latent heat flux, SLHF (u–x); surface sensible heat flux, SSHF (y–ab); 10-m wind speed, WSPD (ac–af). Columns: event anomaly; Past analogue composite (1950–1986); Present analogue composite (1987–2024); Present–Past difference. Color-filled areas indicate 95% bootstrap significance. Temperatures are in °C, fluxes in $W m^{-2}$, and wind speed in $m s^{-1}$.

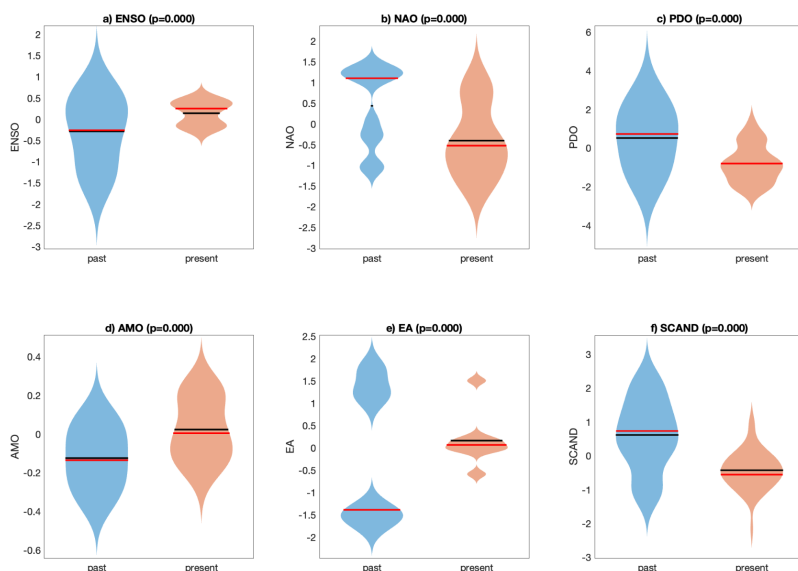


Figure 3. Violin plots comparing the distributions of natural variability indices during analogue dates in the past (1950–1986, blue) and present (1987–2024, orange) periods. The indices include: a) El Niño–Southern Oscillation (ENSO), b) North Atlantic Oscillation (NAO), c) Pacific Decadal Oscillation (PDO), d) Atlantic Multidecadal Oscillation (AMO), e) East Atlantic pattern (EA), and f) Scandinavian pattern (SCAND). Each violin shows the full probability density of the distribution, with horizontal red and black lines indicating the mean and median, respectively. The width of the violin reflects the relative frequency of values. All comparisons yield statistically significant differences between past and present periods (two-tailed Cramér–von Mises test, $p < 0.001$), suggesting that the underlying state of large-scale climate modes has shifted over time.

5. Discussion

The analogue comparison reveals a physically coherent picture: the clearest differences between past and present analogues of the June 2025 MHW lie in the thermodynamic fields — SST itself, near-surface temperature over surrounding land, and incoming shortwave radiation — rather than in the dynamic fields. Sea level pressure, wind speed, latent heat flux and sensible heat flux show weaker, spatially heterogeneous present-minus-past differences with limited basin-wide coherence. This is consistent with the expectation that long-term warming primarily elevates the background thermodynamic state, while the large-scale atmospheric circulation remains more constrained by internal variability that has not yet shifted significantly over the observational record. It complements recent work showing that concurrent atmospheric heatwaves and

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a supprimé: In summary, the analogue framework shows that the 2025 marine heatwave did not require an anomalously new circulation pattern; rather, it occurred under a pattern that has historical precedents but unfolded over a present-day background that systematically enhances heat storage at the surface. The present composite's higher SST, warmer T2m, greater shortwave input, reduced net longwave loss, and smaller sensible-heat export provide a physically consistent explanation for why events with the same spatial structure now reach higher amplitude. This coherence across independent variables strengthens the attribution of the 2025 event's severity to thermodynamic changes associated with long-term warming.

6. Influence of Natural Variability

To assess the influence of large-scale modes of natural variability on the occurrence and intensity of the 2025 Mediterranean marine heatwave, we analyzed the distributions of six prominent climate indices—El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), East Atlantic pattern (EA) and Scandinavian pattern (SCAND)—computed for the analogue dates in the past and present periods (Fig. 3). These indices represent key modes of internal natural climate variability that modulate regional atmospheric circulation, ocean–atmosphere heat exchange, and storm track positioning, all of which can influence Mediterranean SSTs. The distributions are presented using violin plots, allowing a visual comparison of their spread, central tendency, and overall statistical difference. A two-tailed Cramér–von Mises test confirms that all six indices exhibit statistically significant differences between the past and present analogue sets, with p -values all below the

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weakened surface winds under subtropical ridges can intensify MHW through modified air-sea heat flux exchanges (Bonino et al., 2025; Paredes-Fortuny et al., 2025; Pastor et al., 2024). The relatively weak a spatially incoherent wind speed and turbulent flux differences in the present analogue composites suggest that the 2025 event's exceptional character, such as other recent MHW (Gyuleva et al. 2025, Dong et al. 2025), was not primarily driven by a shift of the large-scale dynamical regime, but rather by the superposition of a recurrent SST anomaly pattern onto a warmer thermodynamic background without any change of variance (Xu et al. 2022) : a warmer ocean, a warmer atmosphere, and more available solar energy reaching a stratified upper-ocean

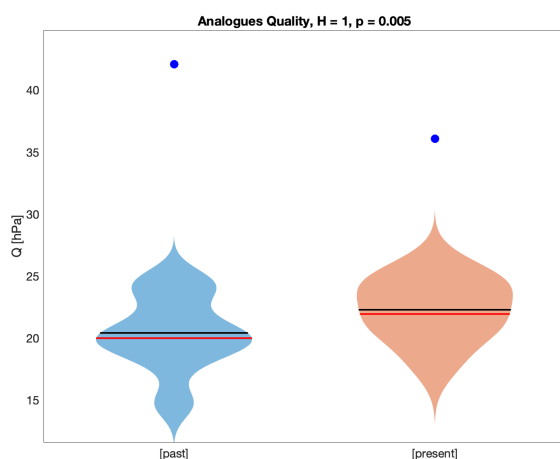


Figure 4. Analogue quality scores (Q) for the set of analogues selected *dates* in the past (1950–1986, blue) and present (1987–2024, orange) periods. Violin plots show the distribution of mean Euclidean distance between 42 analogue SST patterns and randomly selected JJAS days from the same period. The horizontal red and black lines indicate the mean and median of each distribution, respectively. The filled blue dots mark the actual Q values computed between the target 2025 SST event and its selected analogues. A lower Q indicates a better match. The statistical difference between past and present distributions is confirmed by two-tailed Cramér–von Mises test ($p = 0.005$).

The positive SSR differences between present and past analogues are the most spatially coherent and robust signals over the western and central Mediterranean basin. This is consistent with enhanced clear-sky conditions and reduced cloudiness in summer as documented both regionally (Guinaldo et al. 2023, Bonino et al. 2025, Behr et al. 2025) and at a global-scale (Sen Gupta et al. 2020, Goessling et al. 2025) but this point cannot be quantified directly with the present methodology. By contrast, STR differences are spatially heterogeneous and cannot be interpreted as a simple basin wide increase in longwave forcing. Several mechanisms may contribute to the observed radiation patterns, including changes in the thermodynamic state of the lower atmosphere, changes in humidity, and changes in cloudiness. We did not explicitly analyse cloud cover or specific humidity, and multiple mechanisms can contribute to the observed radiation changes including thermodynamic modifications of the lower atmosphere and long-term drying trends. The radiation results are best interpreted as part of a consistent surface energy budget signal rather than as an isolated causal diagnosis. This interpretation should, however, be stated with care. The method does not compare

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a supprimé: One advantage of the analogue method is that it inherently accounts for circulation adjustments and how they interact with thermodynamics (Faranda et al., 2022; Yiou, 2014). Traditional attribution using climate models might, for example, compute a Fraction of Attributable Risk (FAR) for exceeding a certain SST threshold, but might not easily decompose the role of atmospheric patterns. Our analysis indicated that while the large-scale high-pressure pattern was key to the event, its frequency or structure did not vastly change between climates in a way that explains the magnitude difference. In other words, the dynamic setup was necessary but not sufficient for the extreme outcome; the warmer ocean-atmosphere baseline was the decisive factor making the difference between a moderate warm spell and an unprecedented heatwave. This echoes the conclusions of compound event attribution studies: extreme impacts often result from an unlucky alignment of circulation (“weather”) with elevated background conditions (“climate change”) (Vautard et al., 2016; Faranda et al., 2023). The 2025 event exemplifies such a compound, where a northern shift of the subtropical ridge coincided with record-high baseline SST and air temperatures. Our analogues confirm that this mechanism alone, in a cooler world, would not have yielded the observed extremes. It is important to address uncertainties and assumptions inherent in our methodology. First, the selection of period (1950–1986 vs 1987–2024) is somewhat arbitrary; the earlier period still exhibits some degree of anthropogenic warming relative to pre-industrial conditions. Then, if a truly “pure” pre-industrial analogue would be available, the observed differences could potentially be more pronounced. However, ERA5 does not extend before 1940, and observational analogues are then limited. Our past period can thus be seen as a conservative estimate of the counterfactual cooler climate. Another consideration is the stationarity of analogues: we assumed that pattern similarity in SST is a meaningful way to compare events across climates. This assumes no entirely new pattern emerged due to climate change that has no precedent. For the SST field, this is likely valid – the spatial structures of anomalies are governed by geography and ocean dynamics that are relatively stationary (e.g., west vs east Mediterranean differences often relate to wind patterns like the Mistral, etc.). We did find analogues, implying the 2025 pattern was not meteorologically unique in shape, just in amplitude. If climate change had introduced a qualitatively new state (a “black swan” event outside the range of analogues; Faranda et al., 2022), our method might struggle or signal poor analogue quality. The analogue distances in our case were moderate, not extremely high, suggesting the event was an intensification of known patterns rather than a never-seen-before configuration – which justifies using analogues for attribution. One limitation of our approach is that we did not explicitly account for changes in stratification and mixed layer depth (MLD). These factors influence the ocean’s ability to store and redistribute heat, and could therefore modulate the intensity of extreme events. However, the potential impact is likely limited in our case: although the long-term trend in the Mediterranean MLD points toward a shoaling, the depth remains very shallow in summer and is

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identical atmospheric or coupled ocean atmosphere states. It compares atmospheric and surface conditions associated with similar SST anomaly patterns. The results therefore support a conditional statement. In the later part of the historical record, SST patterns resembling the June 2025 event are associated with stronger marine warming and, in several regions, with stronger atmospheric warming and stronger shortwave input than in the earlier part of the record. This is consistent with thermodynamic amplification in a warmer climate background, but it is not a complete attribution proof on its own.

A first-order quantification of the conditional shift can be obtained directly from the analogue composites in Figure 2. Over the grid points where the present-minus-past difference is significant at the 95% level after bootstrap and FDR correction, the SST shift typically reaches +1 to +1.5 °C across broad sectors of the western Mediterranean and parts of the Adriatic, while T2m shifts over surrounding land are of comparable to larger magnitude, locally in the +1.5 to +2.5 °C range over the Iberian Peninsula, southern France, Italy and the Balkans. The corresponding present-minus-past SSR differences are of order a few W m^{-2} over much of the western and central basin. These figures should be interpreted as conditional metrics: they describe the typical shift of the thermodynamic environment in which SST patterns analogous to the June 2025 event occur, and not as a probabilistic attribution estimate of the human contribution to the 2025 event itself. Internal variability associated with the different distributions of low-frequency modes sampled by the two analogue populations (Figure 3) can also contribute to these magnitudes, which is why we present them as ranges rather than as point estimates.

Compared to formal probabilistic attribution based on CMIP-class model ensembles, the SST-analogue framework offers complementary, rather than redundant, information for an event such as the June 2025 Mediterranean MHW. Model-ensemble attribution typically targets a scalar return-period or risk-ratio change in a regional SST or MHW index. Here, by holding the SST anomaly pattern approximately constant by construction, we obtain spatially resolved, multi-variable composite differences for SST, T2m, MSL, SSR, STR, SLHF, SSHF, and WSPD, all from observation-constrained reanalysis fields. This disaggregation makes it possible to identify which surface energy budget terms shift most coherently between past and present analogue populations — in this case clearly SST, T2m and SSR — and which terms remain weak and spatially heterogeneous — here MSL, STR, SLHF, SSHF and WSPD. CMIP-based attribution can quantify the risk-ratio, but does not provide this kind of variable-by-variable, grid-point-resolved diagnostic of the analogue environment for one specific event. The two approaches are therefore best used jointly, as already suggested by hybrid frameworks combining observational analogues with large ensembles.

The shifts in ENSO, PDO, AMO, EA, and SCAND distributions indicate an important and complex interaction in the observational analogue method: the analogue populations are embedded in different low frequency variability states. The observed present minus past differences reflect a combination of externally forced long-term warming and changes in internal variability. It is a key aspect of every attribution study in order to separate such shifts from the externally forced signal. Numerous methods have been proposed (Trenberth et al. 2015, Naveau et al. 2020, Otto 2023) to overcome these limitations and sample in the best way possible the decennial to multi-decennial variability including the use of Large Ensemble (Deser et al. 2020) or the UNSEEN methods (Atkins et al. 2025). The observed differences provide a physically interpretable signal, but they cannot be partitioned into forced and unforced components. As such, hybrid approaches that combine observational analogues with large ensemble model diagnostics could help address this in future work.

A second important limitation concerns ocean dynamics. Our analysis does not explicitly include ocean advection, mixed layer depth, vertical mixing, or subsurface heat content. These processes can be important in the Mediterranean, and in some seasons or subregions they may substantially modulate the onset, intensity,

or persistence of marine heatwaves. The omission is less severe in the summer Mediterranean than it would be in other contexts because stratification is typically strong and mixed layers are shallow and less variable in summer (d'Ortenzio et al., 2005; Juza et al., 2022). Even so, ocean dynamical contributions cannot be ruled out and the present study should not be interpreted as a full process closure of the 2025 event.

A key assumption of the analogue method is that variable structures remain physically sufficiently comparable across climate states meaning that a pattern of SST anomalies in 1980 represents a dynamically similar configuration to the same pattern in 2020, differing primarily in background changes. In the Mediterranean Sea, the basin geometry and recurrent large scale forcing constrain the broad spatial organization of anomalies make this assumption plausible. Nevertheless, long-term warming can modify the magnitude of SST anomalies and their west east gradients, which may reduce the representativeness of historical analogues, especially when recent extremes are compared with earlier decades (Marullo et al., 2011; Pastor et al., 2020; Pisano et al., 2020). The analogue quality analysis confirms that the 2025 event lies toward the upper end of analogue distances in both periods, indicating that the event is only partially captured even by its best historical analogues. This also illustrates the limits of this approach alone as attribution evidence.

Within these limits, the analogue analysis provides an event specific observational comparison of the environmental context associated with similar SST anomaly patterns in two parts of the historical record. It therefore complements the broader literature showing that Mediterranean MHWs are intensifying under climate change by showing, for this particular event, where and in which variables the past and present analogue contexts differ most strongly.

6. Conclusions

The Mediterranean Sea experienced one of its most intense early-summer MHWs on record in June 2025. Using an SST analogue framework, in which the target of the analogue search is the observed SST anomaly pattern itself, applied to ERA5 reanalysis data covering 1950–2024, we have compared the atmospheric and surface energy budget conditions associated with historical SST patterns appearing like the June 2025 event across two climate periods: a past period (1950–1986) and a present period (1987–2024). This distinguishes the study from the more usual circulation first analogue approach and is better aligned with the marine nature of the event.

Three main findings emerge from the analysis. First, the June 2025 event was exceptional in the observational record, with the strongest SST anomalies concentrated in the western Mediterranean, locally exceeding +4.5 to 5.5°C, and with elevated temperatures extending over much of the basin.

Second, the analogue comparison reveals a clear thermodynamic fingerprint of long-term warming. Present-period analogues of the 2025 SST pattern are systematically associated with stronger SST anomalies, warmer near-surface air temperatures over surrounding land areas, and greater incoming shortwave radiation than past-period analogues. These differences are spatially coherent and statistically significant across broad portions of the basin. By contrast, differences in sea level pressure, wind speed, latent and sensible heat fluxes, and longwave radiation are weaker and spatially heterogeneous, indicating that the dominant shift between earlier and more recent climate backgrounds lies in the thermodynamic environment rather than in a change of the associated large-scale circulation.

Third, the analogue framework demonstrates both its utility and its limitations for marine heat extreme event attribution. It provides a physically transparent, observation-based, and event-specific line of evidence consistent with thermodynamic amplification of the 2025 MHW in the context of long-term Mediterranean warming. It cannot, however, fully disentangle contributions of the externally forced warming from internal variability, and it does not resolve ocean dynamical processes that may have contributed to the event's onset and persistence.

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More generally, the study shows that SST analogue comparisons offer a valuable complement to model-based attribution for marine extremes. Their observational grounding, and event-specific objectives make them well-suited for rapid scientific assessments following major events. Future developments of this approach should explore its combination with large climate model ensembles to explicitly disentangle forced and internal contributions, and its extension to include subsurface ocean variables to better capture the role of ocean dynamics in MHW intensification.

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Data availability

ERA5 reanalysis data used in this study are publicly available from the Copernicus Climate Data Store. The Mediterranean Sea High Resolution L4 Sea Surface Temperature Reprocessed product is available from the Copernicus Marine Service Information (<https://doi.org/10.48670/moi-00173>). All derived data supporting findings of this study are available from the corresponding author upon reasonable request.

Code availability

The analogue analysis workflow builds on publicly available functions implemented in the ClimateMe framework (Faranda et al., 2024). Custom scripts used in this study are available from the corresponding author upon reasonable request.

Author contributions

D.F. designed the study and coordinated the analysis. T.G. and F.P. provided data and analysis observational datasets. T.G., F.P. and S.K. provided expertise on Mediterranean marine heatwaves and contributed to interpretation. T.A. contributed to methodological development. All authors discussed the results and contributed to writing and revising the manuscript.

Competing interests

The authors declare no competing interests.

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References

- Adloff, F., Somot, S., Sevault, F., Jordà, G., Aznar, R., Déqué, M., ... & Gomis, D. (2019). Mediterranean Sea response to climate change in an ensemble of twenty first century scenarios. *Climate Dynamics*, 45(9), 2775-2802.

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- Alberti, T., Faranda, D., Rapella, L., Coppola, E., Lepreti, F., Dubrulle, B., & Carbone, V. (2024). Impacts of changing atmospheric circulation patterns on aviation turbulence over Europe. *Geophysical Research Letters*, 51, e2024GL111618. <https://doi.org/10.1029/2024GL111618>
- Alexander, M. A., Bladé, I., Newman, M., Lanzante, J. R., Lau, N. C., & Scott, J. D. (2002). The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. *Journal of Climate*, 15(16), 2205-2231.
- Artana, C., Kaplan, A., Ramírez, F., Ortega, M., Steenbeek, J. G., & Coll, M. (2026). Marine heatwaves are transforming Western mediterranean marine ecosystems. *Scientific Reports*.
- Banzon, V., Smith, T. M., Steele, M., Huang, B., & Zhang, H. M. (2016). Improved estimation of proxy sea surface temperature in the Arctic. *Journal of Atmospheric and Oceanic Technology*, 33(11), 2499-2499.
- Behr, L., Xoplaki, E., Luther, N., Josey, S. A., & Luterbacher, J. (2025). Atmospheric patterns drive marine heatwaves in the North Atlantic and Mediterranean Sea during summer 2023. *Environmental Research Letters*, 20(10), 104020.
- Bonino, G., McAdam, R., Athanasiadis, P., Cavicchia, L., Rodrigues, R. R., Scoccimarro, E., ... & Masina, S. (2025). Mediterranean summer marine heatwaves triggered by weaker winds under subtropical ridges. *Nature Geoscience*, 18, 1-6.
- Capotondi, A., Rodrigues, R. R., Sen Gupta, A., Benthuyssen, J. A., Deser, C., Frölicher, T. L., ... & Wang, C. (2024). A global overview of marine heatwaves in a changing climate. *Communications Earth & Environment*, 5(1), 701.
- Chen, X., & Tung, K. K. (2014). Varying planetary heat sink led to global warming slowdown and acceleration. *Science*, 345(6199), 897-903. <https://doi.org/10.1126/science.1254937>
- Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben Rais Lasram, F., Aguzzi, J., ... & Voultsiadou-E. (2010). The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. *PloS one*, 5(11), e11842.
- Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J. P., Iglesias, A., ... & Xoplaki, E. (2018). Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, 8(11), 972-980.
- Darmaraki, S., Somot, S., Sevault, F., Nabat, P., Cabos Narvaez, W. D., Cavicchia, L., ... & Sein, V. (2019). Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics*, 53(10), 1371-1392.
- Darmaraki, S., Denaxa, D., Theodorou, I., Livanou, E., Rigatou, D., Raitos, D., ... & Parasiris, (2024). Marine heatwaves in the Mediterranean Sea: A literature review. *Mediterranean Marine Science*, 25(3), 586-620.
- D'Andrea, F., Duvel, J. P., Rivière, G., Vautard, R., Cassou, C., Cattiaux, J., ... & Yiou, P. (2023). Summer deep depressions increase over the Eastern North Atlantic. *Geophysical Research Letters*, 51(5), e2023GL104435.

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- Deser, C., Lehner, F., Rodgers, K. B., Ault, T., Delworth, T. L., DiNezio, P. N., ... & Ting, M. (2023). Insights from Earth system model initial-condition large ensembles and future prospects. *Nature climate change*, 10(4), 277-286.
- d'Ortenzio, F., Iudicone, D., de Boyer Montégut, C., Testor, P., Antoine, D., Marullo, S., ... & Madec, G. (2005). Seasonal variability of the mixed layer depth in the Mediterranean Sea as derived from situ profiles. *Geophysical Research Letters*, 32(12), L12605.
- Dong, T., Zeng, Z., Pan, M., Wang, D., Chen, Y., Liang, L., ... & Zhang, D. (2025). Record-breaking 2023 marine heatwaves. *Science*, 389(6758), 369-374.
- Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E., & Wimmer, W. (2012). The operational sea surface temperature and sea ice analysis (OSTIA) system. *Remote Sensing Environment*, 116, 140-158.
- England, M. H., Li, Z., Huguenin, M. F., Kiss, A. E., Sen Gupta, A., Holmes, R. M., & Rahmstorf, S. (2025). Drivers of the extreme North Atlantic marine heatwave during 2023. *Nature*, 639, 1-8.
- Estaque, T., Richaume, J., Bianchimani, O., Schull, Q., Mériot, B., Bensoussan, N., ... & Garrabou, J. (2023). Marine heatwaves on the rise: One of the strongest ever observed mass mortality event in temperate gorgonians.
- Faranda, D., Messori, G., & Yiou, P. (2020). Diagnosing concurrent drivers of weather extremes: Application to warm and cold days in North America. *Climate Dynamics*, 54(3-4), 2187-2200. <https://doi.org/10.1007/s00382-019-05106-3>
- Faranda, D., Bourdin, S., Ginesta, M., Krouma, M., Noyelle, R., Pons, F., Yiou, P., & Messori, G. (2022). A climate change attribution retrospective of some impactful weather extremes of 2021. *Weather and Climate Dynamics*, 3(4), 1311-1340. <https://doi.org/10.5194/wcd-3-1311-2022>
- Faranda, D., Messori, G., Jézéquel, A., Vrac, M., & Yiou, P. (2023). Atmospheric circulation compounds anthropogenic warming and impacts of climate extremes in Europe. *Proceedings of the National Academy of Sciences*, 120(3), e2214525120. <https://doi.org/10.1073/pnas.2214525120>
- Faranda, D., Coppola, E., Alberti, T., Vrac, M., Pons, F., Yiou, P., et al. (2024). ClimaMet: Contextualizing extreme weather in a changing climate. *Weather and Climate Dynamics*, 5(3), 959-983. <https://doi.org/10.5194/wcd-5-959-2024>
- Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Cassou, C., ... & Zhai, P. (2025). Indicators of global climate change, 2024: Annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data Discussions*, 2025, 1-72.
- Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, 560(7718), 360-364.
- Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M., Schlegel, R., ... & Harmelin, J. (2022). Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biology*, 28(19), 5708-5725.
- Giorgi, F. (2006). Climate change hot-spots. *Geophys. Res. Lett.*, 33, L08701. [doi:10.1029/2006GL025734](https://doi.org/10.1029/2006GL025734).

- a mis en forme ... [52]
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- Goessling, H. F., Rackow, T., & Jung, T. (2025). Recent global temperature surge intensified by record low planetary albedo. *Science*, 387(6729), 68-73.
- Guinaldo, T., Voldoire, A., Waldman, R., Saux Picart, S., & Roquet, H. (2023). Response of the sea surface temperature to heatwaves during the France 2022 meteorological summer. *Ocean Science*, 19(3), 629-647.
- Guinaldo, T., Cassou, C., Sallée, J. B., & Liné, A. (2025). Internal variability effect doped by climate change drove the 2023 marine heat extreme in the North Atlantic. *Communications Earth & Environment*, 6(1), 291.
- Gyuleva, G., Knutti, R., & Sippel, S. (2025). Combination of internal variability and forced response reconciles observed 2023-2024 warming. *Geophysical Research Letters*, 52(14), e2025GL115270.
- Hersbach, H., Bell, B., Berrisford, P., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999-2049. <https://doi.org/10.1002/qj.3803>
- Hobday, A. J., Alexander, L. V., Perkins, S. E., et al. (2016). A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, 141, 227-238. <https://doi.org/10.1016/j.pocean.2015.12.011>
- Holbrook, N. J., Scannell, H. A., Sen Gupta, A., et al. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications*, 10(1), 2624. <https://doi.org/10.1038/s41467-019-10206-6>
- Holbrook, N. J., Sen Gupta, A., Oliver, E. C., Hobday, A. J., Benthuyssen, J. A., Scannell, H. A., ... Wernberg, T. (2020). Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment*, 1(9), 482-493.
- Juza, M., Fernández-Mora, A., & Tintoré, J. (2022). Sub-regional marine heat waves in the Mediterranean Sea from observations: Long term surface changes, sub surface and coastal responses. *Frontiers in Marine Science*, 9, 785771.
- Laufkötter, C., Zscheischler, J., & Frölicher, T. L. (2020). High impact marine heatwaves attributable to human-induced global warming. *Science*, 369(6511), 1621-1624. <https://doi.org/10.1126/science.aba0690>
- Lionello, P., & Scarascia, L. (2018). The relation between climate change in the Mediterranean region and global warming. *Regional Environmental Change*, 18(5), 1481-1490. <https://doi.org/10.1007/s10113-018-1290-1>
- Marullo, S., Artale, V., & Santoleri, R. (2011). The SST multidecadal variability in the Atlantic, Mediterranean region and its relation to AMO. *Journal of Climate*, 24(16), 4385-4401.
- Martínez, J., Leonelli, F. E., García-Ladona, E., Garrabou, J., Kersting, D. K., Bensoussan, N., ... Pisano, A. (2023). Evolution of marine heatwaves in warming seas: The Mediterranean Sea case study. *Frontiers in Marine Science*, 10, 1193164.
- Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., ... & Zhou, B. (2022). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
- Naveau, P., Hannart, A., & Ribes, A. (2020). Statistical methods for extreme event attribution in climate science. *Annual Review of Statistics and Its Application*, 7(1), 89-110.

- a mis en forme ... [81]
- a supprimé: Faranda, D. (2023). A methodology for ... [84]
- a supprimé: *Climate Dynamics*, 61(1-2), 229–253 ... [86]
- a mis en forme ... [82]
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- a supprimé: the
- a mis en forme ... [111]
- a déplacé (et inséré) [9]
- a mis en forme ... [112]
- a supprimé: 16

1493 • Oliver, E. C. J., Donat, M. G., Burrows, M. T., et al. (2018). Longer and more frequent marine
1494 heatwaves over the past century. *Nature Communications*, 9(1), 1324. <https://doi.org/10.1038/s41466-018-03732-9>

1495 • Otto, F. E. L. (2016). The art of attribution. *Nature Climate Change*, 6(4), 342-343. <https://doi.org/10.1038/nclimate2971>

1496 • Otto, F. E. (2023). Attribution of extreme events to climate change. *Annual Review of Environment and*
1497 *Resources*, 48(1), 813-828.

1498 • Paredes-Fortuny, L., Pastor, F., & Khodayar, S. (2025). Concurrent atmospheric heatwaves intensify
1499 marine heatwaves through air-sea heat flux change in the Mediterranean Sea. *Communications Earth*
1500 *& Environment*, 6, 638. <https://doi.org/10.1038/s43247-025-02633-2>

1501 • Pastor, F., Valiente, J. A., & Khodayar, S. (2020). A warming Mediterranean: 38 years of increasing
1502 sea surface temperature. *Remote Sensing*, 12, 2687.

1503 • Pastor, F., & Khodayar, S. (2023). Marine heat waves: Characterizing a major climate impact in the
1504 Mediterranean. *Science of the Total Environment*, 861, 160621.

1505 • Pastor, F., Paredes-Fortuny, L., & Khodayar, S. (2024). Mediterranean marine heatwaves intensify
1506 the presence of concurrent atmospheric heatwaves. *Communications Earth & Environment*, 5(1), 79.
1507 <https://doi.org/10.1038/s43247-024-01982-8>

1508 • Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C., Leonelli, F. E., ... & Buongiorno Nardelli, B. (2020). New evidence of Mediterranean climate change and variability from sea surface temperature
1509 observations. *Remote Sensing*, 12(1), 132.

1510 • Sen Gupta, A., Thomsen, M., Benthuisen, J. A., Hobday, A. J., Oliver, E. C. J., Alexander, L. V., ... & Wernberg, T. (2020). Drivers and impacts of the most extreme marine heatwave events. *Scientific*
1511 *Reports*, 10, 19359. <https://doi.org/10.1038/s41598-020-75445-3>

1512 • Seneviratne, S. I., Zhang, X., Adnan, M., et al. (2021). Weather and climate extreme events in a
1513 changing climate. In *Climate Change 2021: The physical science basis* (IPCC AR6 WGI, Chapter 1).
1514 Cambridge University Press. <https://doi.org/10.1017/9781009157896.013>

1515 • Shepherd, T. G. (2016). A common framework for approaches to extreme event attribution. *Current Climate Change Reports*, 2(1), 28-38. <https://doi.org/10.1007/s40641-016-0033-y>

1516 • Smale, D. A., Wernberg, T., Oliver, E. C. J., et al. (2019). Marine heatwaves threaten global biodiversity
1517 and the provision of ecosystem services. *Nature Climate Change*, 9(4), 306-311. <https://doi.org/10.1038/s41558-019-0412-1>

1518 • Smith, K. E., Burrows, M. T., Hobday, A. J., Sen Gupta, A., Moore, P. J., Thomsen, M., ... & Smale, D. A. (2021). Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*, 374(6566), eabj3593.

1519 • Stott, P. A., Christidis, N., Otto, F. E. L., et al. (2016). Attribution of extreme weather and climate-related
1520 events. *Wiley Interdisciplinary Reviews: Climate Change*, 7(1), 23-41. <https://doi.org/10.1002/wcc.3593>

1521 • Sutton, R. T., & Hodson, D. L. R. (2005). Atlantic Ocean forcing of North American and European
1522 summer climate. *Science*, 309(5731), 115-118.

a mis en forme ... [113]
a mis en forme ... [114]
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- Trenberth, K. E., Fasullo, J. T., & Shepherd, T. G. (2015). Attribution of climate extreme events. *Nature climate change*, 5(8), 725-730.
- Tuel, A., & Eltahir, E. A. B. (2020). Why is the Mediterranean a climate change hot spot? *Journal of Climate*, 33, 5829-5843.
- van Garderen, L., Feser, F., & Shepherd, T. G. (2021). A methodology for attributing the role of climate change in extreme events: A global spectrally nudged storyline. *Natural Hazards and Earth System Sciences*, 21(1), 171-186. <https://doi.org/10.5194/nhess-21-171-2021>
- Vautard, R., Yiou, P., Otto, F., Stott, P., Christidis, N., van Oldenborgh, G. J., & Schaller, N. (2018). Attribution of human-induced dynamical and thermodynamical contributions in extreme weather events. *Environmental Research Letters*, 11(11), 114009.
- Wernberg, T., Thomsen, M. S., Burrows, M. T., Filbee-Dexter, K., Hobday, A. J., Holbrook, N. J., ... & Smith, K. (2025). Marine heatwaves as hot spots of climate change and impacts on biodiversity and ecosystem services. *Nature Reviews Biodiversity*, 1-19.
- Wilks, D. S. (2016). The stippling shows statistically significant grid points: How research results are routinely overstated and overinterpreted, and what to do about it. *Bulletin of the American Meteorological Society*, 97(12), 2263-2273.
- Xu, T., Newman, M., Capotondi, A., Stevenson, S., Di Lorenzo, E., & Alexander, M. A. (2022). Increase in marine heatwaves without significant changes in surface ocean temperature variability. *Nature Communications*, 13(1), 7396.
- Yiou, P. (2014). AnaWEGE: A weather generator based on analogues of atmospheric circulation. *Geoscientific Model Development*, 7(2), 531-543. <https://doi.org/10.5194/gmd-7-531-2014>

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