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# Mediterranean marine heatwaves intensify in the presence of concurrent atmospheric heatwaves

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Under climate change, temperature extremes have become more frequent and intense in recent decades, both in the atmosphere and in the ocean with devastating impacts on ecosystems and succeeding socioeconomic consequences. This is particularly true in climate change hotspots such as the Mediterranean region, where spatiotemporal compounding of extreme phenomena is becoming the norm. In the framework of a new spatiotemporal approach to heatwave detection, which tracks the evolution of the phenomena throughout their life cycle, the concurrence of marine and atmospheric heatwaves is investigated in this study. Concurrency of both phenomena in time and space shows a relevant impact on the intensity of the marine heatwaves, while no relevant changes are observed in atmospheric heat waves. Therefore, we demonstrate that intensification in extreme temperature events is accompanied by the added local intensification effect of marine heatwaves when concurring with atmospheric heatwaves, especially in recent years.

In the last decades, global warming induced by climate change has led to an intensification of extreme temperature events in both land and ocean environments at a global scale<sup>1</sup> and, particularly, in the Mediterranean region<sup>2,3</sup>. Regarding recent trends for extreme atmospheric temperatures<sup>4</sup> it has been found that the probability of devastating global-scale heat waves will increase drastically, which cannot be explained without human-induced climate change. At the global scale, there is evidence<sup>1</sup> of an increase in the number of warm days and nights and an increase in extreme temperatures, at least since 1950, and that this increase is consistent in central and southern Europe, western Asia and northern Africa. Atmospheric heat waves (AHWs) have also become more frequent and intense, and the number of heatwave days has experienced a significant increase in Europe<sup>1,5</sup> and northern Africa<sup>5,6</sup>. Moreover, marine heat waves (MHW) are also becoming more frequent and longer at a global scale<sup>7,8</sup> and their foreseeable evolution in climate change scenarios will lead to global substantial increases in their duration and intensity<sup>9</sup>, mainly due to mean sea surface temperature (SST) increases<sup>10,11</sup> but also to SST seasonal variability changes<sup>12</sup>. MHWs have been associated with major impacts on areas such as ocean biodiversity and economy<sup>13–16</sup> or sea level<sup>17</sup>. Regarding their impacts on marine life, several studies state that MHWs pose more substantial threats to large marine ecosystems<sup>18,19</sup>. Other recent studies have analysed the compounding of MHWs and biological extreme events such as low chlorophyll events<sup>20</sup> assuming that the latter can exacerbate the impacts of MHWs on marine life.

The Mediterranean region is widely considered as a hot spot for climate change<sup>21,22</sup> whose acceleration has exacerbated its regional environmental impacts that will also probably increase in future scenarios<sup>23</sup>. The Mediterranean area falls among the regions with the largest trends for summer temperature extremes around the globe<sup>24</sup> leading to a new situation where the present HW-days could be the norm by the end of the present century with a large increase in AHWs intensity and duration in the Mediterranean<sup>25</sup>. AHWs have progressively magnified or increased in frequency in the last decades in the Iberian Peninsula<sup>2</sup>, with an acceleration in that increase in the last two decades, Southern Europe<sup>26</sup> and northern Africa<sup>6</sup>. Among the impacts associated with the increase in temperature extremes in the Mediterranean basin, the frequency and extent of large wildfires have increased and are projected to worsen under future scenarios due to heat-induced fire-weather types<sup>27</sup>. Public health is another crucial sector that has been impacted by temperature rise<sup>28,29</sup> and AHW intensification in the Mediterranean; an evaluation of the mortality attributable to heat in Spain in the summer of 2022 showed excess mortality due to extreme heat around 4600 deaths<sup>30</sup> while northern Africa is one of the regions with a higher percentage excess in mortality due to temperature variability and western Asia has been qualified between the regions with a higher increasing rate of temperature variability-related mortality<sup>31</sup>. In the warming Mediterranean Sea<sup>32,33</sup>, MHWs have also experienced an increasing trend, regarding frequency and intensity in the last 40 years<sup>34</sup> that has notably accelerated in the last two decades<sup>35</sup> due to SST warming trend<sup>36</sup> both at the

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sea surface and subsurface<sup>37</sup> and are also projected to intensify under different climate scenarios with a very likely increase in spatial coverage, duration, and severity<sup>38</sup>. Among other impacts, massive mortality events have been associated with MHWs in the Mediterranean<sup>39,40</sup>, aside from other multiple and complex impacts on marine life<sup>41,42</sup> which have also been associated with MHWs in the Mediterranean highly concerning the intense ocean stratification found in the development of these phenomena<sup>43</sup>.

Extreme climatic phenomena have been extensively studied by the research community but there are fewer studies regarding the concurrence between atmospheric or atmospheric and oceanic events, despite the growing interest in the research community in the study of compounding and/or cascading events<sup>44–47</sup> because of the possible additive effect leading to bigger impacts than the ones for stand-alone extreme events. Recent research has analysed MHWs and droughts' common causes<sup>48</sup> while other still scarce studies paid attention to individual AHW and MHW events to look for common drivers, interactions, and impacts of coincident terrestrial and marine HW events<sup>49,50</sup>. Regarding the compounding between atmospheric and marine HW events, very few studies can be found over the oceans, while coupling of terrestrial AHWs and MHWs is starting to receive some attention at regional scale. A study in South Africa<sup>49</sup> found an association between land temperature anomalies, wind anomalies, and MHWs in coastal waters. Some regional studies have recently shown the potentially severe impacts that the concurrence of atmospheric and marine HW events can provoke; concurrent terrestrial AHWs and MHWs have been shown to have an impact through a series of pervasive and spatially extensive biotic disruptions in Western Australia with high species mortality in both land and sea<sup>51</sup>. Co-occurrence rates of terrestrial and marine HWs on pairs of land coastal and adjacent ocean cells have been studied<sup>52</sup>, where co-occurring HW days were defined as the days in which an MHW completely encompassed a terrestrial HW, finding a significant increase in the number of terrestrial heatwave days with a co-occurring MHW along the coasts of Australia. Interestingly, it has been found<sup>53</sup> that the compound effects of an oceanic mixing event and a following AHW were responsible for an increased ocean heat content offshore Florida. Recently, a new study has analysed the co-occurrence of terrestrial AHWs and MHWs to assess their impact on drought and wildfires in the Mediterranean region<sup>54</sup> and found a strong positive correlation between terrestrial air temperature and SST. Although the mentioned studies have investigated the concurrence between AHWs and MHWs, they are limited to terrestrial AHWs and very few studies have run concurrent assessments, to our knowledge, over the ocean. Regarding the spatial co-occurrence of AHWs and MHWs over the sea, co-occurrence in the Eastern Mediterranean (EMED) has been analysed<sup>55</sup>, with the co-occurrence of HWs considered when an AHW was completely encompassed by an MHW event at a single grid point. They found a statistically significant correlation between AHWs and MHWs frequencies and total days in the EMED, but with regional differences; they also found an increase in the co-occurrence of AHW and MHW events frequency and total days.

Air-sea heat fluxes are considered essential drivers of the climate system<sup>56</sup> driving ocean-atmosphere exchanges across scales that are closely related to SST and its anomalies<sup>57</sup>. The air-sea interface heat fluxes are among the drivers intervening in the onset, development, and decay of MHWs<sup>58,59</sup> in different regions<sup>50,60–63</sup>. In the Mediterranean Sea, MHWs have been related, but not only, to calm winds and increased heat fluxes<sup>58</sup>; a Mediterranean case study<sup>34</sup> for MHWs in 2019 associated them with a large atmosphere-to-ocean heat flux in the Western Mediterranean (WMED) while in the EMED, SST anomaly caused an anomalous upward flux. Recently, MHWs and latent heat flux in the surface heat budget of extreme marine summers have also been assessed finding a major role of surface fluxes in the northern half of the Mediterranean Sea while oceanic processes have a greater contribution in the southern regions<sup>64</sup>.

As the relevant impact of the atmosphere-ocean heat exchange in MHWs has been extensively studied in the recent scientific literature, it is of great interest to study this interaction in more detail in the case of extreme atmospheric and oceanic conditions, such as AHWs and MHWs, due to the

plausible amplification of their impacts. The extraordinary 2003 Mediterranean AHW and MHW events and their possible interaction received attention through many studies<sup>65,66</sup> which found that high Mediterranean SST reinforced the European AHW once it started, although it did not play a role in its onset. Regional case studies analysed the relationship between the 2003 terrestrial AHW major event and Mediterranean SST. Another study in the Ligurian Sea<sup>67</sup> showed that the anomalous SST warming in the Ligurian Sea was mostly due to calm atmospheric conditions and the absence of wind that led to limited vertical mixing and strong stratification with very warm water in a thin surface layer. Similar results were obtained from experimental and model data for the Central Mediterranean<sup>68</sup> relating the excess heating to an increase in air temperature, a decrease in the wind stress, and a reduction of the upward heat flux, mainly affecting the top marine layers<sup>55</sup>.

Most scientific literature about AHWs and MHWs share a commonly used methodology to address their characterisation and run easy and comparable analyses worldwide. Both types of events are defined as prolonged periods of high temperature in which atmospheric temperature or SST exceeds a threshold based on predefined climatology. Nevertheless, many different definitions for HWs have been used in the scientific literature with slight differences on the thresholds, minimum duration, reference climatology or use of detrended temperature data<sup>54,69,70</sup>, especially in the context of global change. Regarding temporal extension for HWs, an AHW is considered when, at least, three consecutive days show temperature values above a certain threshold<sup>69</sup> while five consecutive days are needed to define an MHW<sup>71</sup>. Even though the Hobday definition has been widely used in the research community, there is still an open discussion about a single common MHW definition<sup>72</sup> on the use of detrended SST time series<sup>36</sup> or the selection of fixed or moving climatology baselines<sup>72,73</sup>. Some authors have used a spatial extension threshold in their MHW analysis, such as the 20% of the Mediterranean basin to analyse only large summer MHW events<sup>3</sup> but others introduced a minimum extension to consider SST extremes as MHWs<sup>35</sup>. More recently other authors<sup>74</sup> built a database of MHW macro events in the Mediterranean Sea by aggregating spatiotemporally connected MHW events greater than 100,000 km<sup>2</sup>, accounting for 25% of the Southern Europe and Western Asia basins. A different approach to analyse the spatiotemporal distribution and evolution of MHW was done by calculating an activity index<sup>75,76</sup> that aggregates intensity, duration and size of the events. On a global scale, a parameter-based methodology to follow the spatiotemporal evolution of the largest MHWs, i.e. with a minimum spatial extension of 5° × 5°, was developed based on a minimum overlapping area, without a fixed universal overlap but which should in any case be less than 70%, at consecutive time steps<sup>77</sup>. This methodology is not applicable to marginal seas, like the Mediterranean, because of the too large spatial extent needed to identify an event as an MHW.

During the last decades, meteorological extremes have become more frequent and intense under climate change, which has led to a growing corpus of scientific literature around them. The frequency increase of extreme events consequently leads to a higher probability of their compounding or cascading as well as their probably intensified impacts<sup>78</sup>. Studies on the compounding of MHW and other extremes, such as sea level rise, algal blooms or massive mortality events and on the influence MHWs can have in terrestrial AHWs can be found in the literature but compounding of AHWs and MHWs over the oceans is a still not in-depth studied question. So, the overarching aim of this study is to improve our understanding of the compounding of AHWs and MHWs, understood as the spatiotemporal coincidence of both phenomena, and analyse the impact the compounding may have on their main characteristics. To this end, and further contributing to the open discussion on the MHW definition and detection, a new spatiotemporal approach to MHW detection has been developed for the Mediterranean, but easily expandable to other ocean basins, which tracks the evolution of the event throughout its whole life cycle and, in addition, a definition of concurrency between AHWs and MHWs has also been developed providing new tools for extreme temperature events analysis.

## Results

### MHW and AHW characterization and trends in the Mediterranean

The first step of our study was to develop and test a new methodology (see Methods section) for the detection of MHW by considering the spatio-temporal evolution of a dynamic phenomenon that can change its shape, size, and location throughout its life cycle. By applying our methodology, a total of 344 MHW events were detected for the Mediterranean basin in the 1940–2022 study period. At the Mediterranean scale (Supplementary Table S1), MHWs have a mean duration of 42 days, a mean persistence (number of consecutive days in which a grid point experiences HW conditions) of 16 days, a mean size of around 422,500 km<sup>2</sup> (roughly 17% of the Mediterranean basin) and mean maximum size of 722,500 km<sup>2</sup> (almost 29% of the basin). Regarding MHW intensity, its mean intensity ( $I_{\text{meanM}}$ ) is 1.19 °C while the mean maximum intensity ( $I_{\text{maxM}}$ ) reaches 1.46 °C at the whole basin scale. Mean MHW cumulative intensity ( $I_{\text{cumM}}$ ) presented a value of 28.90 °C-days. Our  $I_{\text{meanM}}$  and  $I_{\text{cumM}}$  values are comparable but somewhat lower than the 1.60 °C and 24.70 °C-days values for the shorter 1982–2021 period in ref. 35 which could indicate that the MHW intensity is not dependent on the detection algorithm, while the mean duration of MHWs is almost three times larger in this new approach, as expected. The use of a 20-year fixed and moving climatology baselines to detect MHWs led to mean intensity values of 1.90 °C and 1.60 °C respectively<sup>73</sup> 13 and 18 days mean duration values comparable to other studies<sup>35</sup> or slightly lower than the 20-day value for summer MHWs<sup>3</sup> but, again, far below our results. To evaluate the impact of the reference period used in our results, mean MHW characteristics have been calculated with a different 30-year climatology, 1991–2020. Results in Supplementary Table S2 show that the main impact is on a lower number of detected MHWs and a reduced mean duration and persistence. When comparing intensities of the days classified as MHW with both references, the mean intensity for the 1961–1990 period is higher than for the 1991–2020 reference, as expected, but the opposite pattern is found when considering the full population of MHW days. Mean intensity for the full set of MHWs from the 1961–1990 reference shows slightly lower values than those found with the new reference period. This behaviour is because the days excluded with the more recent reference show a notably lower intensity than the ones retained as MHW days with both reference periods (Supplementary Table S3). The 1991–2020 reference retained a shorter set of stronger intensity MHW events leading to a higher global mean value. Despite these changes in intensity, the maximum values of duration, persistence, and size are still found in the EMED, while maximum values for intensities occur in the Adriatic Sea (ASEA), as with the 1961–1990 reference. Notably, the trends for  $I_{\text{meanM}}$ / $I_{\text{maxM}}$  show slightly lower/higher values but still positive and greater for  $I_{\text{maxM}}$  than  $I_{\text{meanM}}$  as for the 1961–1990 reference period.

In the case of AHWs their mean size is roughly 15% of the Mediterranean, which accounts for approximately 371000 km<sup>2</sup>, and have a mean duration of 12 days and a mean persistence of 6 days. Their mean intensity ( $I_{\text{meanA}}$ ) is 0.86 °C, with a maximum value reaching 2.30 °C, while the maximum intensity ( $I_{\text{maxA}}$ ) presents a mean value of 1.60 °C and a maximum of 3.78 °C. Regarding air temperature values, the mean value for the spatial mean of maximum temperature ( $T_{\text{max}}$ ) is 25.80 °C while the mean value for minimum temperature ( $T_{\text{min}}$ ) is 23.40 °C.

However, as the results shown in the previous paragraph are basin-averaged values, they could mask regional variability. To better assess spatial variability, the same analyses were also run in the areas shown in Supplementary Fig. S1 and results presented in Supplementary Table S1. For AHWs, the highest mean intensity values were found in the ASEA but higher mean temperatures, both  $T_{\text{max}}$  and  $T_{\text{min}}$ , were recorded in the EMED. Longer lasting and larger mean AHW events were found in the EMED but showed the lowest maximum intensities. MHWs were also more intense ( $I_{\text{meanM}}$  and  $I_{\text{maxM}}$ ) in the ASEA but with the highest mean size and duration in the EMED, coinciding with previous studies<sup>35</sup>, as was the case of the AHWs, and consequently also with the highest  $I_{\text{cumM}}$  mean values. Regarding MHWs' mean persistence (Supplementary Fig. S2), the highest values are also found in the EMED, with maximum values in the Libyan

coast and the southeasternmost areas of the basin, while ASEA and WMED show lower values with less regional variability.

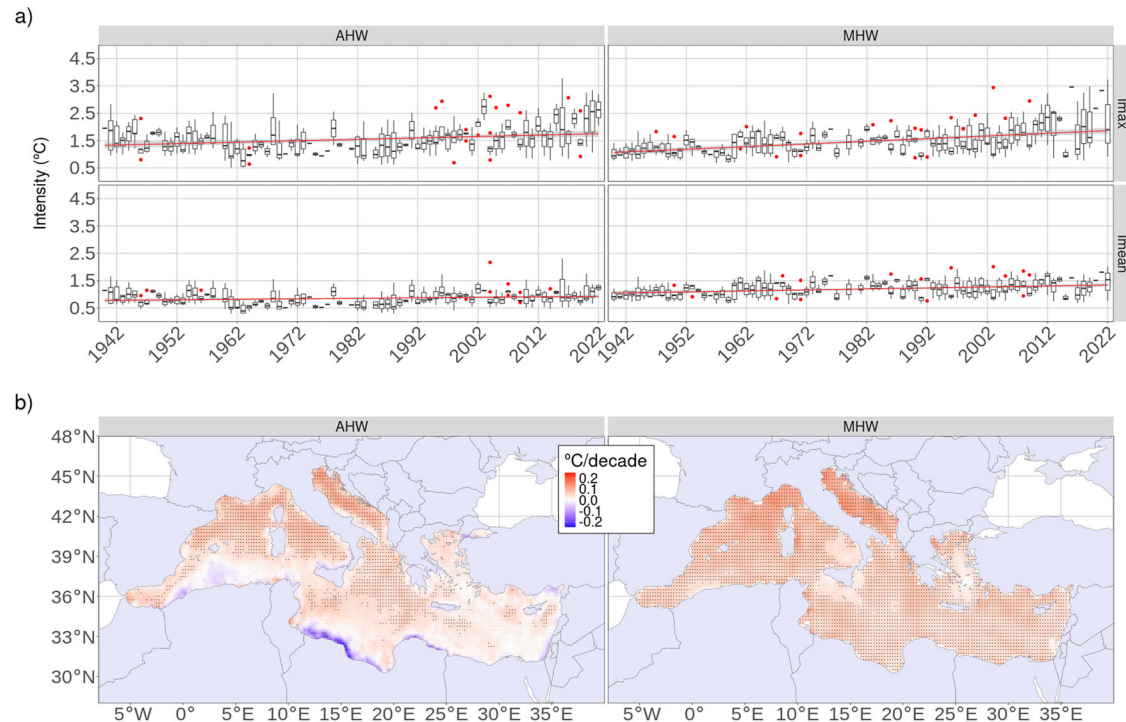
Aside from the characterization of AHW and MHW events, an analysis of their temporal evolution was run for  $I_{\text{mean}}$  and  $I_{\text{max}}$  for the 1940–2022 study period. Figure 1a shows AHWs and MHWs mean intensity annual trend (with significance above 99%). In the case of AHWs, there is a very weak positive decadal trend for  $I_{\text{meanA}}$  ( $0.02 \pm 0.01$  °C/decade) while  $I_{\text{maxA}}$  trend ( $0.06 \pm 0.02$  °C/decade) is stronger, also showing greater variability in intensity values. MHWs also show a stronger trend for  $I_{\text{maxM}}$  ( $0.13 \pm 0.01$  °C/decade) than the one for  $I_{\text{meanM}}$  ( $0.04 \pm 0.01$  °C/decade) as in the case of AHWs. In both cases, AHWs and MHWs,  $I_{\text{max}}$  shows a more pronounced increasing trend, and greater variability, in the last decades, which is not so noticeable for  $I_{\text{mean}}$ . To assess the robustness of our methodology in MHW detection, linear trends for duration and intensity were evaluated for a different period (1982–2022) to compare with the recent satellite observed trends. The linear trend found for  $I_{\text{meanM}}$  was  $0.03 \pm 0.03$  °C/decade, close to the  $0.02$  °C/decade<sup>3</sup> for the largest summer events in the 1982–2017 period but lower to the  $0.06$  °C/decade trend for 1982–2020<sup>34</sup>. The weak trend for  $I_{\text{meanM}}$ , which was not statistically significant, agrees with trends for 1982–2021<sup>35</sup>, which concluded there was not a global trend for the Mediterranean but differentiated subregional trends ranging from areas with a slightly negative trend to a maximum of  $0.30$  °C/decade. Conversely,  $I_{\text{maxM}}$  showed a significant (above 99%) positive trend of  $0.13 \pm 0.01$  °C/decade at the basin scale. This trend is notably weaker than the  $0.26$  °C/decade<sup>36</sup> found for a different baseline climatology (1982–2021) while subregional values ranged from  $0.10$  to  $0.40$  °C/decade<sup>35</sup> but match well with the  $0.12$  °C/decade trend<sup>34</sup>. A major disagreement appears in the trend of MHW duration as a  $13 \pm 3$  days/decade trend was obtained, slightly more than twice the value of 5 days/decade in 1982–2021<sup>35</sup> or three times lower than the 3.6 days/decade in °C/decade trend<sup>34</sup> in 1982–2020. This divergence from values previously obtained in the scientific literature was foreseeable as the new methodology necessarily implied an increase in the duration of events and a consequent decrease in annual frequency. Even so, it is noteworthy that there is a noticeable degree of similarity in terms of the MHW intensity trend with previous work by other authors, despite the different detection methodologies.

To analyse their spatial variability, the decadal trend values of  $I_{\text{mean}}$  for each grid point in the study area are presented in Fig. 1b. Trends for AHW are predominantly positive in most of the Mediterranean Sea, with statistical significance ( $p$ -value  $< 0.01$ ); in contrast, negative trends over the sea are mostly located on northern Africa coastal areas which are not statistically significant. The strongest positive values for the AHW's  $I_{\text{meanA}}$  trend are found in the northern half of the WMED and the ASEA. For MHWs, the Mediterranean Sea shows positive trend values for  $I_{\text{meanM}}$ , which are also statistically significant ( $p$ -value  $< 0.01$ ), with the highest ones in the ASEA, closely followed by the northern half of the WMED. The lowest values were found in the eastern parts of the Aegean Sea and to the north and south of Sicily, also with the lowest statistical significance throughout the Mediterranean basin. The regional variability of  $I_{\text{max}}$  trend has also been assessed (Supplementary Fig. S3) with significant positive values (95% confidence level) in most of the Mediterranean basin. The highest positive trends are found in areas of the Adriatic and Aegean Seas while neutral or negative values are present only in small areas of the WMED, mainly the Gulf of Lyons and parts of the Algerian coast.

### Increase in the frequency of concurrent AHW and MHW events

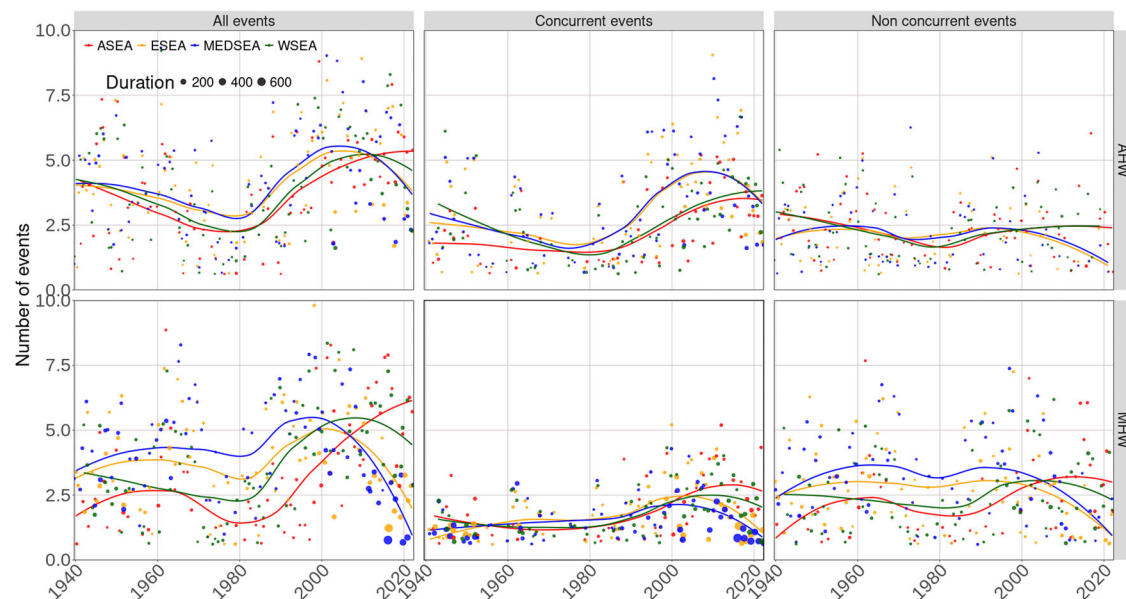
Concurrent AHW and MHW are considered when both events simultaneously occur in the same location. In this sense, the observed positive trend in the number of AHWs<sup>79</sup> and MHWs<sup>35,36,43</sup> in the Mediterranean region should lead to a growing number of concurrent situations (Fig. 2). Indeed, a simple linear regression shows a clear increase in the frequency (number of annual events) of AHWs and an almost neutral trend for MHWs at the Mediterranean scale, but with regional differences for MHWs in which the main increase was found for the ASEA and WMED while EMED shows a weak trend. It has to be noted that in the last decade, there has been a





**Fig. 1 | Annual trends for AHW and MHW intensities.** AHWs and MHWs (a) mean ( $I_{\text{mean}}$ ) and maximum intensity ( $I_{\max}$ ) mean values annual trend with linear regression (shadowed area shows the 95% confidence interval) and (b) regional distribution of  $I_{\text{mean}}$  trend (dots show 99% statistically significant values). All plots

show trends for the 1940–2022 period with reference period 1961–1990. A general positive trend is observed throughout the basin, being more intense for MHWs and especially for maximum intensity.

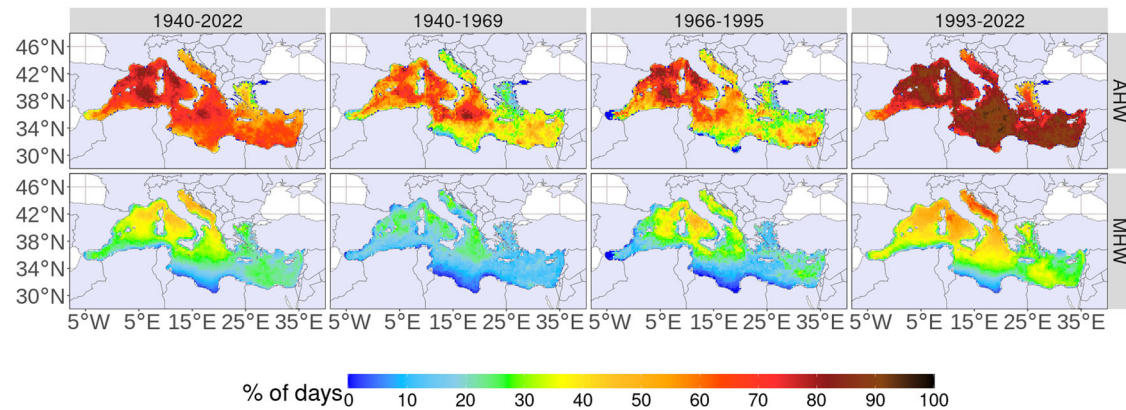


**Fig. 2 | Annual frequency and trend of AHW and MHW events by concurrence type.** Annual number of AHW (May–September) and MHW (all year) events by concurrence type for the Mediterranean and its different subregions (ASEA = Adriatic Sea, WMED = Western Mediterranean, and ESEA = Eastern

Mediterranean). Points size denotes event duration. Concurrent events show an increase for AHWs while MHW concurrent events also increased their frequency and duration.

reduction in the annual frequency of AHW and MHWs at the Mediterranean scale, which is more pronounced in the case of MHWs, conversely to the increase in the annual number of AHW and MHW days. This behaviour, which could seem contradictory with other recent research pointing to more frequent MHWs, is a consequence of the new dynamical definition used in the MHW detection applied in this work leading to longer-lasting

and larger MHW events which then reduce the annual count. This pattern highly increased in the last decade (2010–2022) with the mean decadal duration of 136 days versus the 1940–2022 mean of 45 days and around 1,000,000  $\text{km}^2$  mean size versus a 570,000  $\text{km}^2$  1940–2022 mean. Additionally, to the MHW duration increase already observed, associated with mean SST warming<sup>10,11</sup>, our spatiotemporal approach could integrate



**Fig. 3 | Percentage of May–September AHW-MHW concurrent days.** Regional distribution of AHW and MHW concurrent days from the total AHW (top panel) and MHW (bottom panel) days in the May–September period (from left to right) for

1940–2022 and three 29-year periods (1940–1969, 1966–1995 and 1993–2022). The percentage of concurrent days has progressively increased, especially in more recent decades.

individual minor events separately detected from static grid-point-based approach, but it is also related to the already detected longer duration of MHWs in the Mediterranean<sup>35,36,43</sup>. Regarding the concurrence, there is an increase in the number of concurrent events, especially for the AHWs as MHWs usually have longer duration in the last decades and can encompass more than one AHW in the summer period. It can also be seen an increase in the concurrence mean duration, more markedly in MHWs. At the same time, fully non-concurrent AHW events are slightly becoming less frequent while there are different regional trends for the MHWs which are positive in the WMED and the ASEA and negative in the EMED.

Once the increment of concurrent events had been assessed at a basin scale, regional differences were analysed. Figure 3 shows the percentage of the May–September period concurrent days from the total AHW or MHW days for the whole study period and three equal 29-year subperiods. In the case of concurrent AHWs, the 1940–2022 period shows a mean value for concurrence of almost 62% of the days experiencing AHW but with regional differences. The highest values, reaching 80%, affected almost the whole WMED and areas between Italy and Greece in the EMED, with lower values in the ASEA and the rest of the EMED, especially in the Aegean Sea. The first two subperiods show similar spatial patterns but generally lower concurrence percentage values, around 45% mean in both periods, but in 1993–2022 there was a bloom in the percentage of concurrent AHWs affecting the whole basin with a mean value of 77%. In the case of MHWs and for the whole period, the areas with a higher concurrence percentage are the ASEA and the northern half of the WMED, with a basin mean value of 26% in the 1940–2022 period. For the three subperiods, there is a progressive increase in the mean concurrency value from 15, 21 to 33%, with a stronger increase in concurrent MHWs percentage in the WMED and ASEA in the last decades.

### Intensification of MHWs in the presence of AHWs

From our concurrence definition (see methods section), AHW and MHW events can be classified as fully non-concurrent, partially non-concurrent phase of concurrent events, and concurrent events phase. Figure 4 shows the boxplot and density distribution for  $I_{\text{mean}}$ ,  $I_{\text{max}}$  and  $r_{\text{onset}}$  defined as the rate of temperature change from the start of the event to its maximum intensity<sup>71</sup>, values for both AHW and MHW in the Mediterranean region. For AHWs, all types show similar mean intensity values (0.8–0.9 °C for  $I_{\text{meanA}}$  and 1.3–1.6 °C for  $I_{\text{maxA}}$ ) but slight differences in value distribution, with a rather symmetrical shape/distribution for concurrent and partially non-concurrent events and a higher density of values below the median for fully non-concurrent events. Major differences appear in the case of the concurrent phase of MHW events with clearly higher mean intensity values (1.8 °C for  $I_{\text{meanM}}$  and 2.0 °C for  $I_{\text{maxM}}$ ) than fully non-concurrent ones (1.1 and 1.2 °C respectively). The partially non-concurrent MHW phase shows

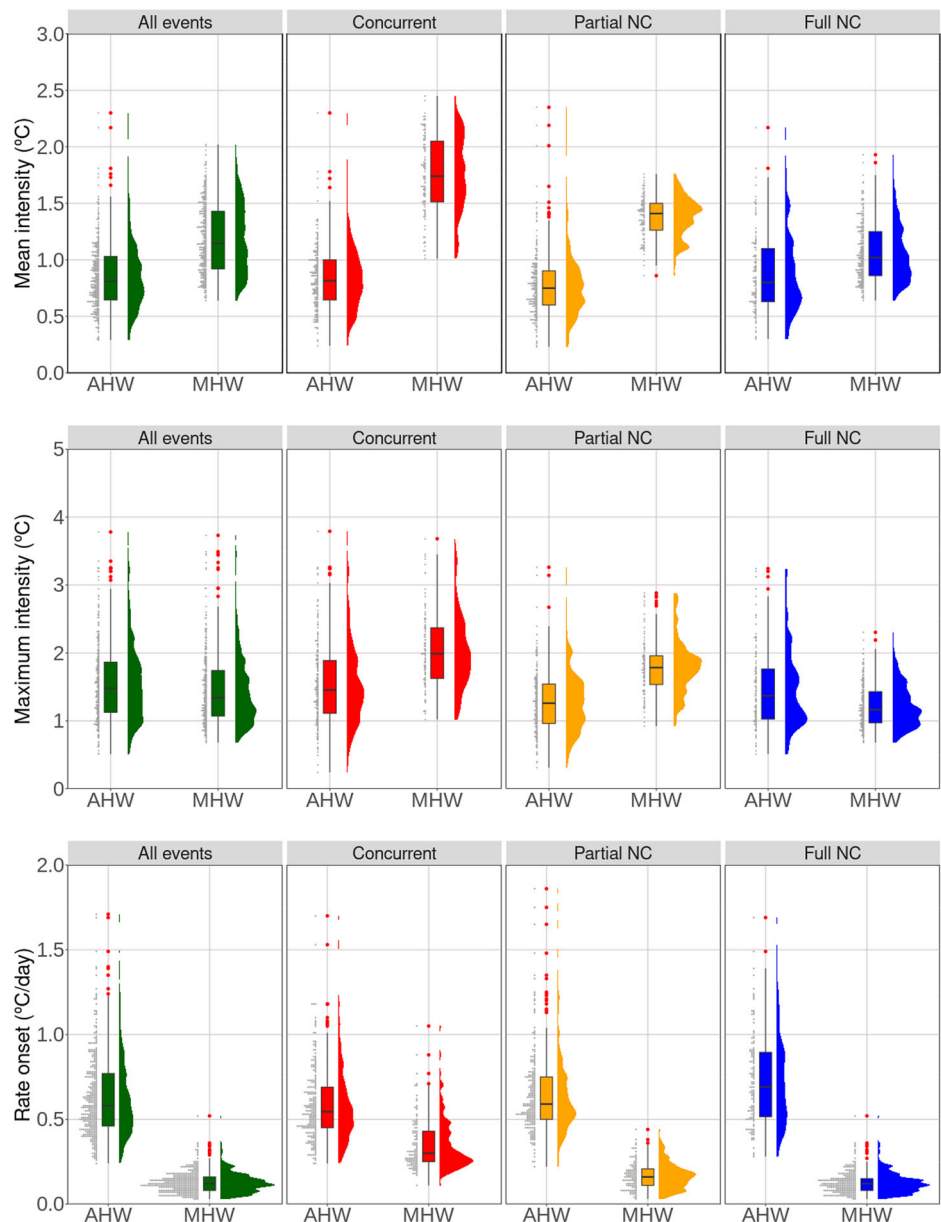
an intermediate step between the other two types (1.4 °C for  $I_{\text{meanM}}$  and 1.8 °C for  $I_{\text{maxM}}$ ), as in the case of AHWs. So, concurrent areas consistently show higher MHW intensities while no significant changes are observed for AHWs  $I_{\text{meanA}}$ , pointing to a major impact of concurrence in MHWs (increasing mean and maximum intensity) rather than in AHWs.

The HWs global intensification presents a growing trend for AHWs and MHWs for the whole Mediterranean and subbasins (Fig. 5) during the study period. Maximum intensity shows a global increase from the beginning of the study period which is more intense since 2000 for the concurrent events and especially for MHWs. For AHWs, a similar variability can be seen for non-concurrent events throughout the study period in all basins, but concurrent ones present larger variability, towards higher values, in the last decades. MHWs non-concurrent events show almost no trend in the long-term while a notable positive trend has been found for concurrent ones since the late 90's decade or 2000, especially in the ASEA where the highest values were observed.

This pattern can also be seen in the probability density function of AHW and MHW days intensity (Fig. 6) which consistently shows that the most probable intensity is higher for the concurrent MHW events and only in the ASEA for AHWs. Similar results are found for the  $r_{\text{onset}}$  metric (Fig. 4) which presents higher values for the concurrent phase to the full non-concurrent MHW events, indicating a faster intensification of the MHW during concurrence (0.4 °C/day), followed by partially non-concurrent phase (0.2 °C/day) and fully non-concurrent events (0.1 °C/day); for AHWs, no important differences are observed (0.6–0.7 °C/day) between the different concurrence categories/phases but with slightly higher values in the case of fully non-concurrent events. Similar patterns are found when analysing concurrence at a regional scale with the highest intensity values and intensification rate for the concurrent phase of MHWs.

The observed impact on MHW intensity in the concurrent areas may probably extend to the non-concurrent areas close to the concurrent ones. To assess if the concurrency impact on MHWs extends towards the non-concurrent areas, the rate of change for daily intensity depending on the distance from the grid points in the outer ring of the concurrent areas was evaluated. Figure 7 shows the mean variation for different concurrent event  $I_{\text{mean}}$  ranges and for distance concerning the intensity of the outer area of the concurrent area. At the lower range of concurrent MHW mean intensity, the intensity difference between the non-concurrent points and the outer concurrent area shows a gradual decrease as the distance from the concurrent area increases. As the concurrent  $I_{\text{meanM}}$  increases, the intensity reduction gets progressively steeper with around a 20% decrease in the first ring around the concurrence area in the highest intensity range. Conversely, for AHWs intensity in the first non-concurrent ring turns out to be somewhat higher than in the concurrent area for the complete data set. Interestingly, this behaviour sharply intensifies in the highest concurrent

**Fig. 4 | Boxplot and density plot of AHWs and MHWs mean intensity ( $I_{\text{mean}}$ , top panel), maximum intensity ( $I_{\text{max}}$ , middle panel and onset rate (bottom panel) for all events and the different concurrency phases. All events (green), irrespective of concurrency, are shown in green. AHW and MHW concurrent events are separated in concurrent (red) and non-concurrent (NC) phases (purple for partial NC and blue for fully NC) categories, concurrency phases, and non-concurrent events (red points denote outliers) in the Mediterranean basin. Points (left) show individual events and the shaded area (right) shows a variable density plot. Concurrent MHWs show an intensification, especially in their concurrent phase.**



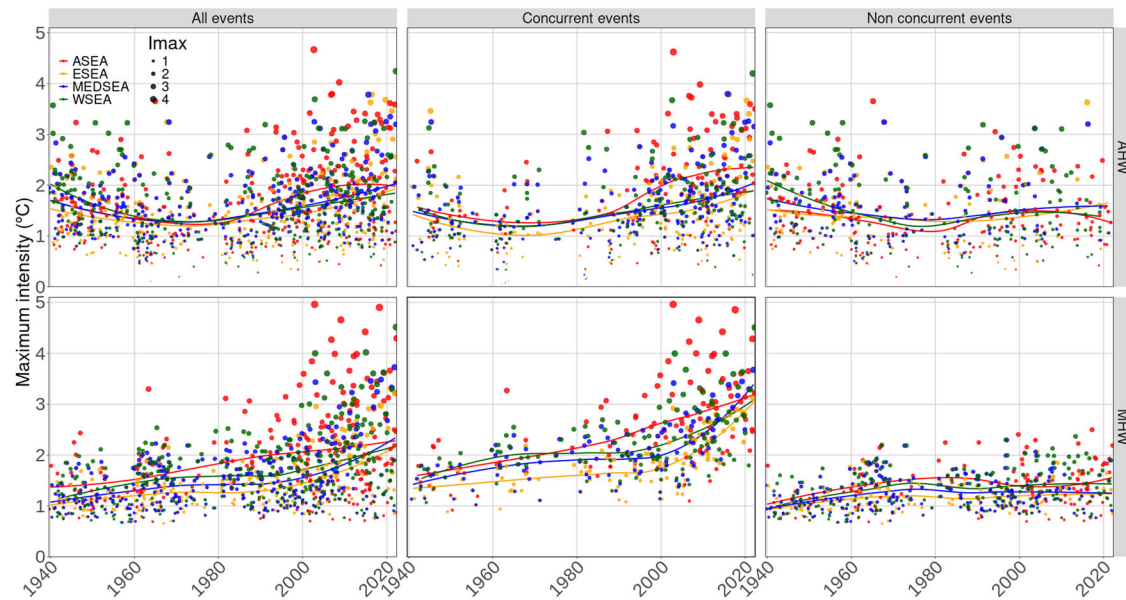
AHW  $I_{\text{mean}}$  ranges, but it does turn to a weak decrease in the lowest ranges. Meanwhile, in the second distance ring the non-concurrent AHW intensity shows values lower than the concurrent area.

## Discussion

Our study aims to better understand the concurrence of atmospheric and oceanic temperature extremes in the Mediterranean region. In the first stage, AHWs and MHWs were characterized for the Mediterranean basin and three subregions by following their spatiotemporal evolution using a novel methodology developed by the authors. Our approach is similar to that of Sun<sup>77</sup> for MHWs at a global scale but applied in a marginal sea like the Mediterranean using setting a minimum area threshold. While Sun<sup>77</sup> prescribed a coarse  $5^\circ \times 5^\circ$  spatial threshold to detect MHWs and a minimum overlapping area to follow spatiotemporal event life cycle, we applied the much smaller 5% of the Mediterranean basin<sup>35</sup> and required spatial continuity for an event to be considered but did not impose an overlapping threshold between consecutive days. As our study was run over a marginal sea with a well-defined basin extension, the requirement for spatial continuity and minimum daily extension builds up a database of MHW days with a very high spatial overlapping ratio (Supplementary Fig. S4) between

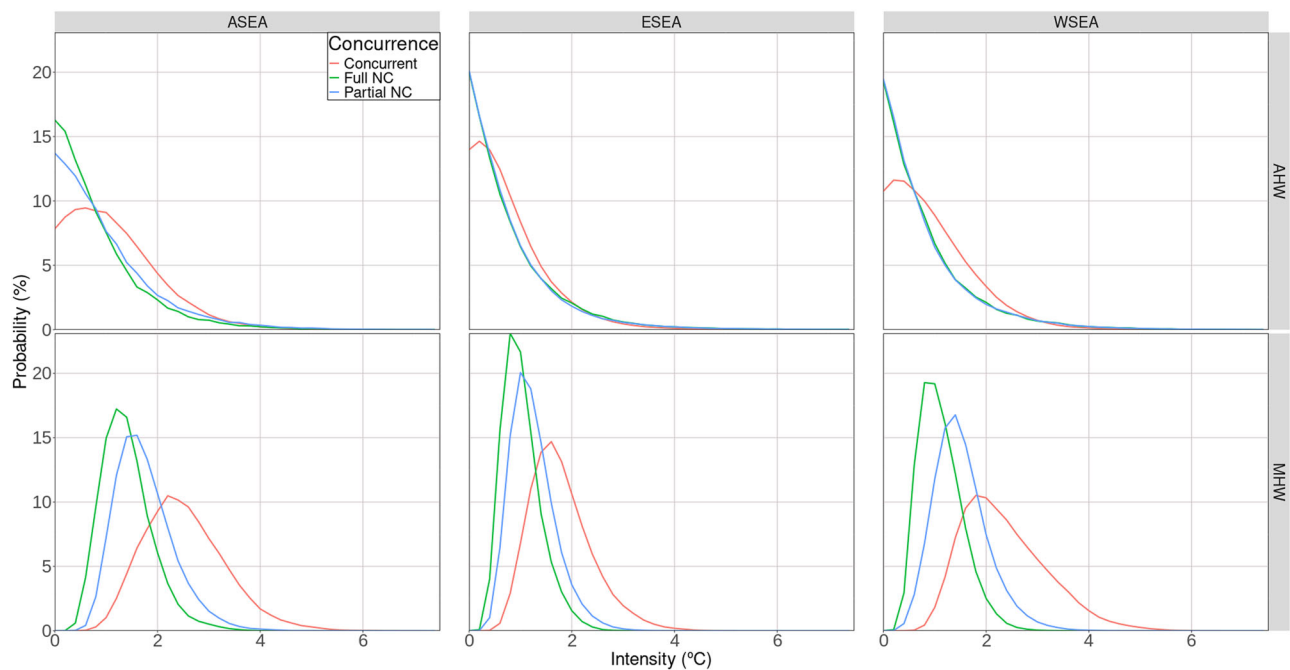
consecutive days likely to be part of an MHW event, showing that the overlapping area is usually bigger than 75%. A possible caveat of our methodology could arise when applying to the global ocean as the areal percentage threshold could affect the number of MHW events detected and their overlapping in large basins. Future studies should investigate the optimal basin extension thresholds for different basins or establish a global minimum area<sup>77</sup>. This new detection methodology opens a different perspective in their analysis since, when considering their temporal evolution, some metrics such as duration or cumulative intensity will tend to be higher than in the mostly used point-based analyses. Hence, the increase in the duration of MHWs, and consequently the increase in cumulative intensity, will be due to both the new definition and the already demonstrated tendency towards MHW intensification<sup>8,35,36,43</sup>. An additional metric to characterise MHW events has been introduced in our analysis, persistence, accounting for the number of consecutive days in which a grid point experiences MHW conditions. In this study, the methodology has been used to detect both MHW and AHW events to work coherently to later analyse their concurrence. Although our approach to MHW event definition and other recent ones<sup>74,77</sup> could help in the discussion of a more general definition of MHWs, we should keep in mind that these definitions are useful





**Fig. 5 | Annual trend of AHW and MHW events maximum intensity by concurrence type.** Annual trend of AHW (May–September) and MHW (all year) maximum intensity by concurrence type for the Mediterranean and its different subregions (ASEA = Adriatic Sea, WMED = Western Mediterranean and ESEA =

Eastern Mediterranean). Points size denotes event intensity. Concurrent events show an increase for AHW and MHW maximum intensity while non-concurrent events show almost no trend.



**Fig. 6 | Probability density function of AHW and MHW daily intensity.** Results are separately shown for the three Mediterranean subbasins and concurrence types. Concurrent MHWs phase shows the highest most probable intensities while fully non-concurrent shows the lowest ones.

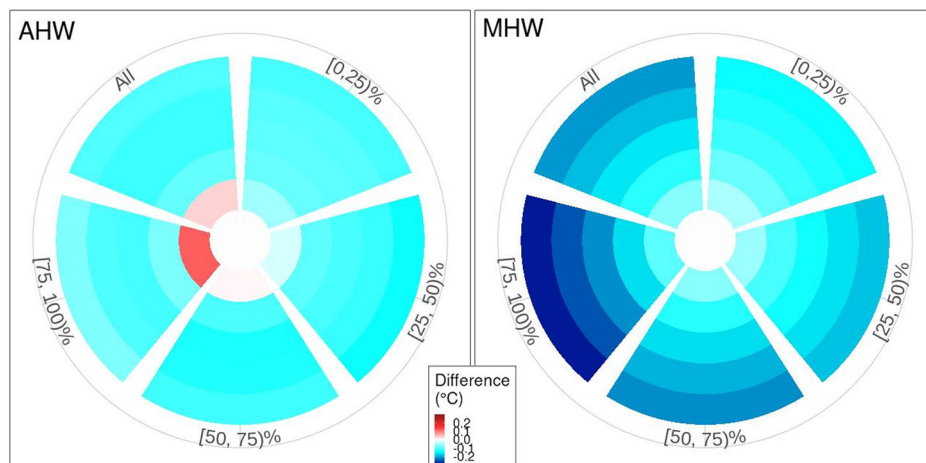
only for their detection at the sea surface, mainly through satellite data, without considering the characteristics or evolution of subsurface MHWs<sup>37,80</sup>.

Regarding the Mediterranean HW events analysis, for AHWs it was found that the most intense events (in mean values) occurred over the ASEA, but the highest temperatures were found in the EMED, where AHW events were also longer lasting and more extensive mainly because of the adiabatic warming, counteracting the Ethesians ventilation effect, and stability induced by large-scale subsidence<sup>81</sup>. Regarding MHWs, the most intense events were recorded in the ASEA but the largest and longest were

observed in the EMED. Trends were evaluated for the HW frequency and main metrics throughout the study period (1940–2022), with a special focus on event intensity. At a Mediterranean basin scale, AHWs mean intensity showed a significantly weak positive trend but a much stronger trend was found for their maximum intensity. A similar pattern was found for MHWs, a maximum intensity trend stronger than the mean intensity one, but with stronger trend values than AHWs. When looking for mean intensity trends at a regional level some differences arise; AHWs show a positive and statistically significant trend in most of the Mediterranean Sea, with stronger values in the ASEA and Northern half of the WMED. In the case of MHWs

**Fig. 7 | Mean AHW-MHW intensity variation (°C) in the areas surrounding the concurrence area.**

Mean intensity variation in °C from the concurrent intensity according to the distance to the concurrence area. Polar sectors show the concurrent intensity percentiles.



most of the basin showed statistically significant positive values for MHW mean intensity, except for the southeastern Tyrrhenian Sea, areas south of Sicily, and the south-central Aegean Sea where positive but not statistically significant values are observed. The MHW intensity stronger trend values were found for the ASEA and the northern half of the WMED, coincident with the same areas where the MHW mean intensity trend was higher in other studies<sup>35</sup>. From a global perspective, it appears that Mediterranean temperature extremes are generally becoming more intense but with regional differences in the speed of these changes. In this sense, the ASEA emerges as a hot spot inside the general AHW and MHW intensification in the Mediterranean basin.

From our concurrence definition, and due to the intensified and more frequent extreme temperature events/days, their concurrence in the Mediterranean Sea/region shows a clear increasing trend throughout the study period while stand-alone events have become progressively less frequent, especially in the last two decades. At a regional level, WMED and ASEA show stronger increasing trends for concurrent events annual frequency while this trend is lower, but still positive, in the ESEA. The trend towards higher concurrence frequency has become stronger since the last decade of the 20th century with a much higher percentage of concurrent days, around 77% of the days of the extended summer experiencing AHW being concurrent and 30% of days being concurrent in the case of the MHWs. For MHWs, the strongest increment of the concurrent days is seen in the ASEA and the northeastern WMED. Hence, concurrent phenomena/events are becoming most frequent in the basin with hot spots in parts of WMED and the ASEA basin.

The concurrence of extreme temperature events could potentially have an impact on their characteristics, mainly due to changes in air-sea heat fluxes<sup>82</sup>. Bearing in mind the concurrence category classification, from fully non-concurrent events to concurrent event phases, mean and maximum event intensities were evaluated for the different categories. While AHW events show no relevant variation in their mean and maximum intensities, important differences appear for MHWs. The average mean and maximum intensity of the concurrent phase of MHW events show higher values than the other event categories, with mean value 0.7–0.8 °C higher than those of fully non-concurrent events. Partially non-concurrent phase intensity of concurrent events is at an intermediate range between the other two categories with values significantly higher, especially for the maximum intensity, than the ones for fully non-concurrent events. These results are obtained both at global and subbasin levels and similar patterns are found for the onset ratio of MHW concurrent events, indicating a faster intensification pace for MHWs in concurrence with AHWs. From these results, the greatest impact of the concurrence of AHW and MHW is reflected in an intensification of MHWs, both in their mean and maximum intensity values and in the speed of their intensification.

The previously mentioned intensification of MHWs, on top of the observed climate change-induced one, appears to be a transient local

phenomenon in the concurrency area. Its possible impact on the surrounding areas has also been assessed from the intensity rate of change as a function of the distance to the concurrent area. It has been observed that MHWs intensity decreases progressively with distance at rates that increase with the mean intensity of the closer concurrent area, which means faster decreases at shorter distances for the most intense MHWs. This reinforces the local character of the MHW intensification associated with the concurrence, which could be due to changes in heat fluxes at the sea-atmosphere interface. Contrary to this, AHWs intensity near the concurrent area turns out to be higher in the highest concurrent AHW intensity range while it is lower in the lowest ranges. This could be due to exacerbated heat transfer from the atmosphere to the sea surface in the case of intense events which could provoke a sharp decrease/increase in AHW/MHW for the most intense concurrent events, but this hypothesis, out of the scope of this analysis, will need to be assessed in future work.

The result obtained in terms of MHWs intensification opens a line of research, outside the scope of this study, that the authors have already initiated towards the analysis of the physical processes at the sea-atmosphere interface in concurrent AHW and MHW events. As stated in Gregory et al.<sup>83</sup>, it is crucial to deepen the actual knowledge of the complex interactions in the atmosphere-ocean system, especially in the extreme temperatures concurrent situations highlighted in this study, to evaluate the possible intensification of heat fluxes in these types of events. This further analysis will rely mainly in exploring the processes and changes in the air-sea energy fluxes in concurrent events but also analysing which synoptic situations are more frequent in these phenomena to assess the role of wind regimes. This should also include the analysis that concurrence has on the environmental and socioeconomic impacts that individual events already have, in order to elucidate whether there is an intensification of these impacts in the case of concurrence.

## Methods

### ERA5 data

ERA5<sup>84</sup> is a comprehensive global reanalysis dataset, currently from 1940 to 5 days behind real time, which assimilates as many observations as possible in the upper air and near-surface. ERA5 reanalysis of the global weather and climate has been developed by the European Centre for Medium-range Weather Forecasting (ECMWF) under the auspices of the EU-funded Copernicus Climate Change Service (C3S). The ERA5 dataset provides hourly estimates for a broad range of atmospheric, ocean-wave and land-surface quantities, which are divided into four distinct subsets. These subsets include hourly products which are available at both pressure levels and single levels, depending on the particular parameter. The data set used here corresponds to the regridded subset to a regular lat-lon grid of 0.25 degrees of the full ERA5 data set on native resolution, which amply satisfies the requirements for the present analyses. The ERA5 variables used in this study are SST and 2-metre temperature from 1940 to 2022 that were accessed in



the MARS archive through the C3S Climate Data Store (C3S-CDS, 2023) facility (<https://cds.climate.copernicus.eu/>). ERA5 temperature data has been found to compare well with observations from station data to assess temperature related mortality<sup>85</sup> and has also been used in AHW analysis in the Mediterranean region<sup>54,86</sup>.

### Detection of AHW and MHW events

In our research MHWs and AHWs have been studied through the period 1940–2022 from ERA5 reanalysis 2 m temperature (T2m) and SST data. Both MHWs and AHWs are well-known extreme temperature events but there is no universal definition of these phenomena; we have used a percentile-based definition for both phenomena but with different persistence criteria and temporal-spatial requirements for atmospheric and marine events. MHWs have been identified throughout the whole year and AHWs only in the extended summer<sup>87,88</sup> (May to September). Recent studies about AHWs in the Iberian Peninsula point out the seasonally dependent nature of these phenomena which has a peak of frequency in the months from July to August but with most recent decades showing a lengthening of the likely occurrence period with a non-neglecting, progressively increasing, number of AHWs in May, June and September<sup>2</sup>. The May–September period selection for AHW analysis and the AHW–MHW concurrence study is also supported by the fact that the air–sea heat flux is, on average, linearly proportional to the product of air–sea temperature difference and wind speed<sup>82</sup>, therefore this flux should be more intense in summer when the air–sea temperature difference tends to be higher due to the high values of T2m.

In the present study, AHWs are defined following the definition of AEMET (the Spanish MetService) in which an extreme temperature event is considered an AHW when the daily maximum temperature at 2m ( $T_{\max}$ ) exceeds the local 95th percentile (P95) for at least three consecutive days affecting at least a certain extension. In our study, we have imposed a spatial requirement of at least 5% of the studied basin to qualify as AHW<sup>26</sup>. AHW events separated by only one day not meeting the AHW conditions are considered the same event. AHWs have been found at each grid point when exceeding the 95th percentile of the May–September climatology for the period 1961–1990, following the recommendations of the WMO. AHW days (AHWD) are defined as the days constituting the AHW event. For the MHWs detection, the Hobday<sup>71</sup> definition has been used in which an MHW event is defined by a gridpoint daily mean SST exceeding the daily 90th percentile of the 1961–1990 climatology for at least five consecutive days, with an additional requirement of a total daily spatial extent equal or greater than 5% of the study basin, following the recommendation for the Mediterranean<sup>35</sup>. To assure the MHW spatial coherence, it is required that for each MHW day, each spatial cluster of contiguous points meeting MHW conditions (i.e. contiguous points with SST > P90 for 5 or more consecutive days) has a size of at least 5% of the Mediterranean. Following the Hobday definition, we have also considered that two MHWs separated by two days or less are the same event. The processing steps of the AHW and MHW detection are analogous and consist of first iteratively imposing the conditions previously described until all of them are met simultaneously. Although we do not prescribe a minimum overlapping area between consecutive AHW/MHW days, the iteratively required spatial continuity filtered out too small events and non-overlapping days hence only retaining AHW/MHW days constituting spatial and temporal continuous and homogeneous events (Fig. 8). Once AHW/MHW events have been determined, a second algorithm is applied to identify their starting/ending dates and characterise their main metrics. With this processing, the whole life cycle of the HW event could be tracked and their spatial continuity assessed. Although we follow a similar spatiotemporal approach to the proposed by Sun<sup>77</sup> there are some differences that should be highlighted. For the spatial continuity Sun uses the K nearest neighbour algorithm, dependent on non-predefined optimal K-parameter, considering an event if more than half of its k-nearest grid cells are identified as MHW irrespective of the total event size but then applying a  $5^\circ \times 5^\circ$  filtering to discard small scale events while in our methodology we look for clusters of contiguous points, without requiring any minimum amount of points, meeting MHW conditions and

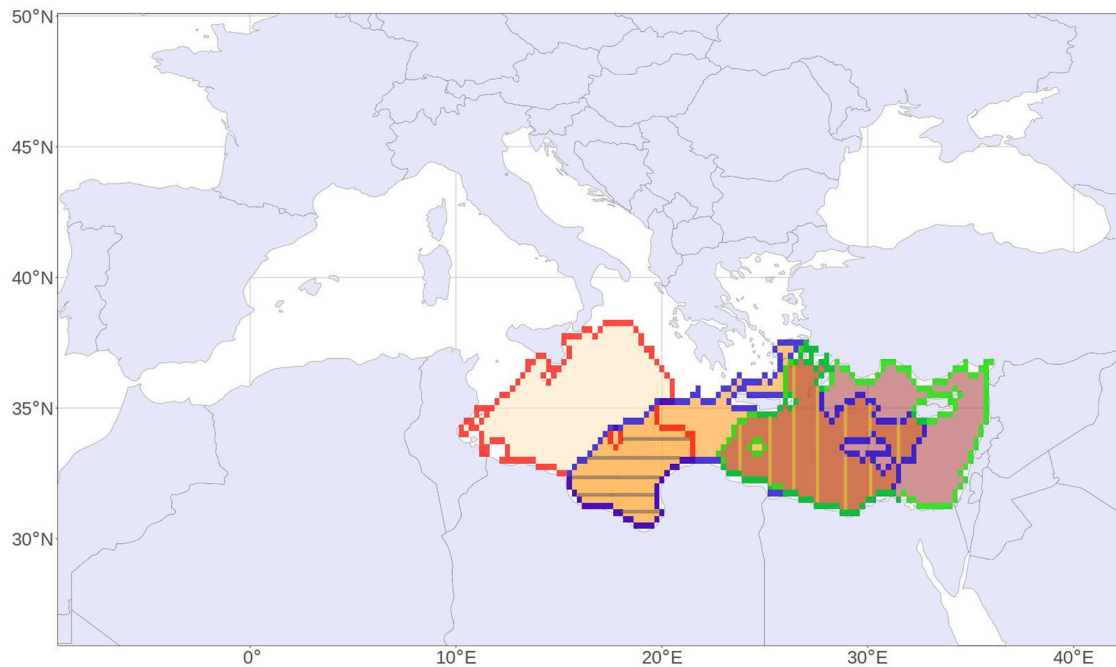
occupying at least 5% of the Mediterranean basin. To assess the temporal continuity of MHWs Sun's method is based on the calculation of the event overlapping area between consecutive days that has to exceed a parameter value ranging from 0 to 1, set to 0.5 in their work but that should not exceed 0.7 as a universal single choice would not be optimal for all MHW events. In our methodology no minimum spatial overlapping is required between consecutive days. The iterative application of the algorithm requiring the minimum spatial size for the MHW event ensures the continuity of the events; the calculation of the probability density function of the overlap yields overlapping areas bigger than 75% (see Supplementary Fig. S4). The application of our methodology relies on the determination of the minimum extent to consider an event, in our case 5% of the Mediterranean, which will have to be re-evaluated especially in larger basins.

Regarding event intensity, a major difference arises in the definition of HW intensity between AHWs and MHWs. In both cases, intensity is a measure of the temperature anomaly, that is, the daily temperature minus a daily reference value computed for the 1961–1990 period. For the AHW the reference is the daily 95th percentile while for the MHW is the daily mean. Thereafter, the intensity of the AHW is by construction larger than the intensity of the MHW. Besides the usual metrics assessed in extreme temperature analyses, a new metric has been introduced for MHW events, persistence, understood as the number of consecutive days in which a grid point experiences MHW conditions. Persistence should be shorter or, at most, equal than duration as the spatiotemporal evolution of the MHW event may end up in a different area from where it started. The ratio between persistence and duration can then be considered as an indicator of the stationarity of the event, ranging from 0 to 1. For yearly analysis and averaging, the MHWs are assigned to the year of the central day of the event so that most of its duration is enclosed in that year, in case an MHW had a duration longer than 1 year.

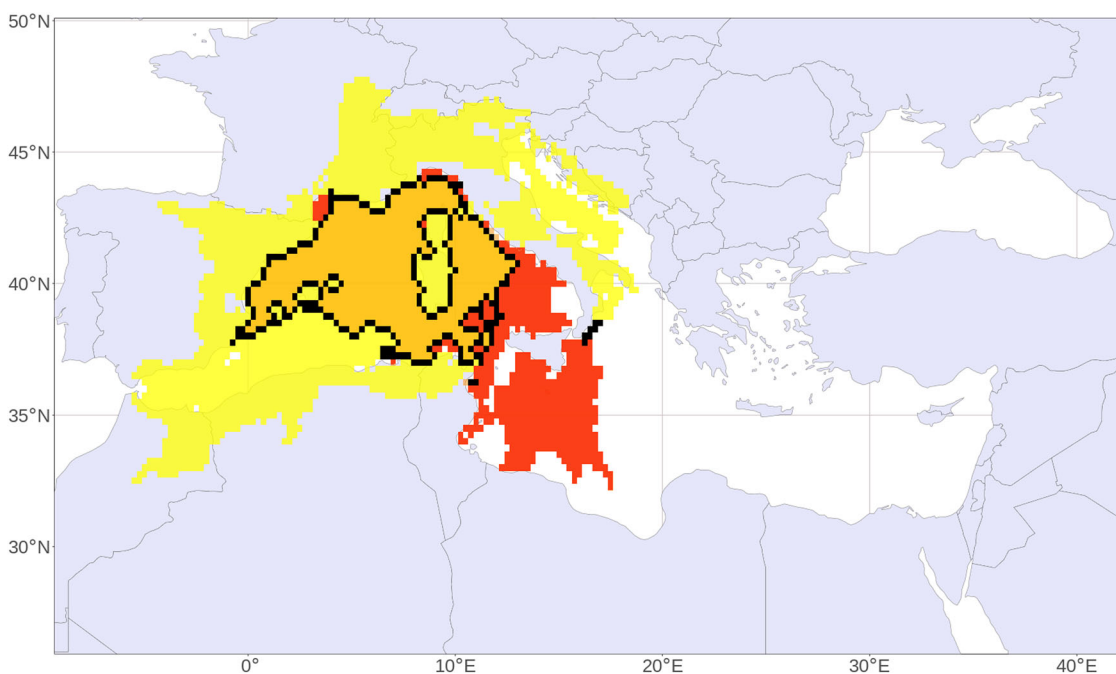
### Definition and detection of concurrence for AMHWs

A previous definition of concurrent events<sup>52</sup> stated that an AHW had to be encompassed by an MHW in coastal and land-adjacent grid points to be considered as concurrent while others<sup>55</sup> do not introduce any explicit spatial requirement by using a grid-point-based approach, aggregating or averaging over all grid cells across the whole study area. In our work, a spatio-temporal approach has been adopted to determine the concurrency of AHW and MHW events. Concurrence is defined as the coincidence of AHW and MHW conditions in the same grid point at least for three days (Fig. 9). This definition of concurrence is independent of the separate AHW and MHW events requirements (i.e. five days minimum duration for MHWs) that had to be independently met before any concurrence analysis. Both types of events can last for a longer period or have a greater spatial extent than the concurrence, so single events can go through concurrent and non-concurrent phases during their respective life cycles and spatial extent. Typically, MHW has a longer duration so a single MHW event can have concurrency with more than one AHW. From this definition, two types of non-concurrent events need to be considered: first the fully non-concurrent events, those not having any concurrent day at any point, and the partially non-concurrent ones, namely the non-concurrent times and areas of concurrent events. Concurrent events are then defined as the phase, in space, of the event where both phenomena coexist at the same time (black contour filled with orange in Fig. 9). Once concurrence is determined, main event characteristics are computed again for the overlapping grid points and days (concurrent phase) and for the rest of the non-overlapping pixels and days (non-concurrent phase, yellow and red areas in Fig. 9) then giving the concurrent and non-concurrent characteristics for the different phases of a single event. The same characteristics analysis has been run for the full events database and the fully non-concurrent events.

As the main study area was the Mediterranean and our main objective was the analysis of AHW and MHW concurrence, the concatenation of temporally coincident but geographically distant MHW events could lead to erroneous detection of “MHW macro-events”, understood as the continuity of days experiencing an MHW event in some part of the basin, that should



**Fig. 8 | Schematic of the MHW spatiotemporal tracking.** Each coloured contour represents a time instant in the evolution of the MHW and the vertical/horizontal lines show the overlapping between different MHW days (blue-green/red-blue contours).



**Fig. 9 | Schematic of the AHW-MHW concurrence.** Example of a concurrent AHW-MHW event. AHW is shown in yellow, MHW in red, and the concurrent area is shown by a black contour filled in orange.

have been considered as distinct events. This could lead to inconsistencies in the analysis of concurrency between MHW and AHW events as well as in their subsequent characterisation because of very small concurrences with separate events. To properly address this issue, a minimum spatial concurrence equal to or greater than 5% of the Mediterranean basin was considered to avoid spurious concurrence. Different lower thresholds were checked obtaining similar results for main event characteristics. Additionally, a division of the Mediterranean basin into three different areas was applied to build a regional MHWs catalogue to be used in further regional

analysis. The three subbasins used in this study are based on previous analysis of MHWs in the Mediterranean basin<sup>35</sup>. From the analysis of the spatiotemporal evolution of MHWs detected in our study, we have chosen three different subbasins: Western Mediterranean, the Adriatic Sea, and joint central and Eastern Mediterranean (Supplementary Fig. S1).

#### Data availability

ERA5 data were obtained from Copernicus Climate Change Service (C3S). ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global

climate. Copernicus Climate Change Service Climate Data Store (CDS), <https://cds.climate.copernicus.eu/cdsapp#!/home> (accessed on 15 March 2023).

## Code availability

The code used for this study is available under request to the corresponding author.

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## Author contributions

All authors contributed to the analysis, discussion, and drafting of this manuscript. F.P. and S.K. conceived the study, L.P.F. developed the code for data analysis and heatwave detection, F.P. was responsible of the data analysis and first draft writing. S.K. and L.P. contributed to manuscript writing and review.

## Competing interests

The authors declare no competing interests.

## Additional information

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