



Trends in ocean waves climate within the Mediterranean Sea: a review

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Abstract

The interest for the impact of climate change on ocean waves within the Mediterranean Sea has motivated a number of studies aimed at identifying trends in sea states parameters from historical multi-decadal wave records. In the last two decades progress in computing and the availability of suitable time series from observations further supported research on this topic. With the aim of identifying consensus among previous research on the Mediterranean Sea and its sub-basins, this review analysed the results presented in peer reviewed articles researching historical ocean waves trends published after the year 2000. Most studies focused on the significant wave height trends, while direction and wave period appear to be under-studied in this context. We analysed trends in mean wave climate and extreme sea states. We divided the Mediterranean basin in 12 sub-basins and analysed the results available in the literature from a wide range of data sources, such as satellite altimetry and numerical models, among others. The consensus on the significant wave height mean climate trends is limited, while statistically significant trends in extreme values are detected in the western Mediterranean Sea, in particular in the Gulf of Lion and in the Tyrrhenian Sea, with complex spatial distributions. Negative extreme sea state trends in the sub-basins, although frequently identified, are mostly not significant. We discuss the sources of uncertainty in results introduced by the data used, statistics employed to characterise mean or extreme conditions, length of the time period used for the analysis, and thresholds used to prove trends statistical significance. The reduction of such uncertainties, and the relationship between trends in sea states and weather processes are identified as priority for future research.

Keywords Ocean waves climate · Climate change · Historical trends · Mediterranean Sea

1 Introduction

The effects of post industrial climate change (CC) on the environment have been investigated by the scientific community since the mid twentieth century. However, the volume of research on the impacts of CC on a wide range of natural physical processes and, in turn, on mitigation measures has

rapidly increased in the 2000s. This is the case of ocean/marine processes, for which a large literature is available on the quantification of historical and future impact of CC on, e.g. water temperature (Meredith and King 2005; Abraham et al. 2013; Wijffels et al. 2016), salinity (Helm et al. 2010; Durack et al. 2012), marine biota (Scavia et al. 2002; Munday et al. 2008), ocean circulation (Toggweiler and Russell 2008; Winton et al. 2013), sea level (Milne et al. 2009; Watson et al. 2015; Chen et al. 2017; Dangendorf et al. 2017, among others), and ocean waves climate. The latter aspect has received increased interest thanks to the relevance of coastal erosion and wave energy conversion in recent years. The much improved computing capacity accessible to research groups worldwide, the availability of extensive numerical databases, satellite observations, and wave projections, have all contributed to the development of a large body of work on the analysis of ocean waves trends that can be detected from time series spanning several decades in the past, hereinafter referred to as historical trends.

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Their analysis is essential to understand the present climate trends.

The topic is of great interest in micro- and meso-tidal environments, such as those found in the Mediterranean Sea (MS), as long-term changes in wave conditions may have strong implications for increased coastal erosion (Satta et al. 2017; Enríquez et al. 2017; Toimil et al. 2020; Simeone et al. 2021) and, in turn, for tourism revenue (Alexandrakis et al. 2015), harbors operation (Casas-Prat and Sierra 2010a; Sánchez-Arcilla et al. 2016) and ships navigation (note that several major ports connect the Mediterranean countries worldwide, making it one of the busiest basins in the world, Mayer et al. 2018), and finally for blue energy production, given that the MS hosts promising hot spots for the conversion of wave energy, see Mattiazzo (2019) and references therein. As such, it is important to provide a broad insight in the wave climate variability in the MS, as well as to identify statistically significant climatic trends.

A large body of research has been devoted to identify historical trends in wave parameters since the 2000s; most of the studies reconstructed multi-decadal time series of ocean waves parameters for the whole MS or one of its sub-basins, from which trends are investigated. The available studies focus on the analysis of trends of the significant wave height H_s , with very few studying other sea states parameters. Even a very quick overview of the literature allows to understand that trends show a rather large spatial variability, with adjacent MS sub-basins sometimes showing opposite behaviour. It is equally evident that the existence of a consensus among these studies is not apparent. Therefore, the aim of the present review is to identify evidence of consistent historical trends of sea states within the MS and its sub-basins. To do so, we analysed the current literature using a top down approach: first we considered articles investigating sea states at whole Earth scale, then at the scale of the whole MS, subsequently we looked into studies of individual or groups of sub-basins; finally, we reviewed articles studying trends at regional or individual locations scale.

This article is organised as follows. Section 2 describes the methodology used for the review. Section 3 describes the trends in H_s found in the literature and identifies the consensus among studies. Section 4 describes sea state parameters other than H_s . Finally, Sect. 5, draws the conclusions of the article and sets out recommendations for future studies on the topic.

2 Materials and methods

For the present review we considered only peer reviewed articles published starting from 2000; indeed, the time span covered by prior researches would be too short for comparison with up-to-date studies; a list of the articles initially

reviewed can be found in the Supplement. Within those we considered only studies that analyse multi-decadal trends in sea states, which excludes, for example, analyses of long term storms characteristics (e.g. Besio et al. 2017; Amarouche and Akpınar 2021). Within the reviewed literature the domain of analysis varies from the whole Earth, to regional studies of stretches of coast of the order of 10^2 km. We refer to *global scale* of analysis to indicate studies that examined the MS as part of a worldwide dataset. Similarly, *regional scale* is used for the analysis of the MS only or, at least, one of the sub-basins into which it is traditionally divided. Finally, *local scale* refers to studies of single locations or coastal stretches. Note that no global scale study was found to discuss sub-basins, due to the coarser resolution used with respect to the other two scales of analysis. The mesh resolution for the numerical simulations used, however, does not consistently increase for local scale studies with respect to regional ones. Studies at regional scale often discuss trends at sub-basin scale, but these are analysed in this review separately from studies in which the focus is purely local.

Wave data series employed in the articles reviewed were retrieved from different sources, such as hindcast and re-analysis with numerical models, satellite altimeters, buoys, pressure transducers, and ship observations (from Voluntary Observing Ships, VOS). Most of the articles reviewed used modelled data (either hindcast or reanalysis; see Fig. 1), as these provided the longest continuous time-series, allowing for sounder trend estimates. A note of caution should be provided in considering trends identified in the literature from studies using multiple data sources or numerical results from different products, or reference periods. For example data availability in time

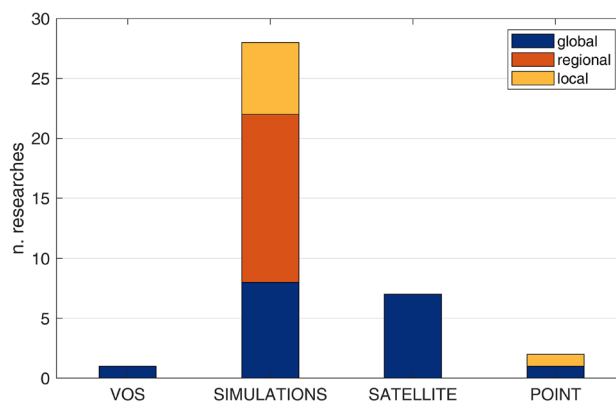


Fig. 1 Data sources used for the analysis of wave parameters in the literature reviewed. Note that the number of sources exceeds the number of articles reviewed because multiple sources are used by some articles. For the sake of clarity, both reanalysis and hindcast are referred as “simulations” (although they differ as the former use ocean wave data assimilation while the latter do not). “Point” denotes point measurements using buoys (Timmermans et al. 2020) and pressure transducers (Pomaro et al. 2017)

series obtained from satellite altimeters, i.e. the density of satellite tracks, was found to affect high percentile trends (Young and Ribal 2022), together with data calibration, i.e. on whether this is performed and what is the benchmark considered. The importance of the specific satellite wave products analysed was also highlighted by Timmermans et al. (2020), who pointed out discrepancies in trend estimates which depend on the data employed. Significant divergences in trend estimates can also be found when comparing hindcast and reanalysis products. As for the latter, modelled wave climate can be greatly affected by data assimilation (Meucci et al. 2020; Erikson et al. 2022). This occurs because there was a significant surge in data assimilated by the models during the early 1990s when satellite assimilation began (Timmermans et al. 2020; Erikson et al. 2022). Furthermore, the trends in model reanalysis are influenced by the growing number of satellite observations assimilated over the years (Sharmar et al. 2021). A further influence on the trends estimate in modelled data using VOS assimilation, may be the lack of standards for measuring surface wind speed in VOS in part of the twentieth century. Even a single model, when initialized with different initial conditions, can yield opposite trends worldwide (Casas-Prat et al. 2022). These factors are crucial when assessing conflicting results, such as opposing trends observed in numerical studies.

Trends were mainly detected using the Mann-Kendall test (Mann 1945; Kendall 1948, hereinafter shortened as MK) and the corresponding seasonal test for monthly averaged series (Hirsch et al. 1982), and were quantified either through linear fit (LF), or the Theil–Sen estimator (Theil 1992, TS), which is based on the Kendall’s rank estimator and it is therefore often used along with MK (the two parameters are in fact well correlated, as shown e.g. in De Leo et al. 2020). Indeed, TS and MK are the most popular methods used to quantify trends and assess their significance, respectively (see Fig. 2). The TS slope allows to filter possible outliers and it is therefore more robust than simple LF, although the two metrics were proved to yield comparable results (Timmermans et al. 2020; Lin and Oey 2019). A group of works assessed trend significance through the Student’s *t*-test (Gulev and Grigorieva 2004; Martucci et al. 2010; Sharmar et al. 2021; Amarouche et al. 2022); the Wilcoxon test, and the test of Hayashi (1982) (Gulev and Grigorieva 2004); an *F*-test (Lionello and Sanna 2005); the time-varying location of a non-stationary Generalised Extreme Value Distribution (De Leo et al. 2021a) denoted with μ_t ; methods based on bootstrap (Casas-Prat and Sierra 2010b, a, 2012; Timmermans et al. 2020); the analysis of LF confidence intervals (CI) (Young et al. 2012); the Innovative Trend Analysis (or ITA; Şen 2012), to be coupled with other trend metrics (Caloiero et al. 2019; De Leo et al. 2020; Lo

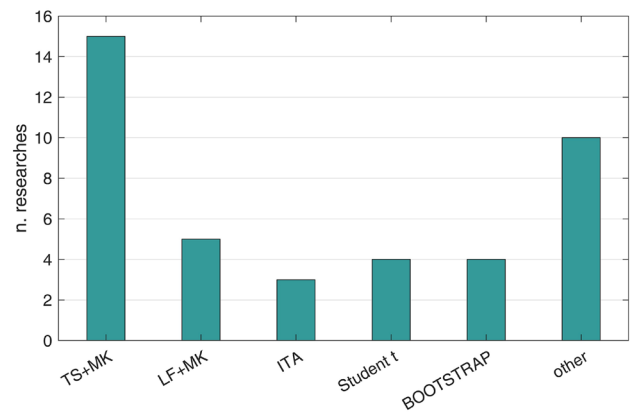


Fig. 2 Number of occurrences of tests employed for trend detection and quantification in the literature reviewed. The group labeled with “other” embeds the tests used only in a single article (Wilcoxon and Hayashi tests, μ_t , *F*-test, either LF or TS with no significance measures). Note that the number of tests exceeds the number of articles reviewed because multiple tests are used in some articles

Feudo et al. 2022). The latter test was proved to be affected by few shortcomings (Serinaldi et al. 2020), thus it should be used with caution.

In order to assess the results on changes in wave climate for each area of the MS, we only considered studies presenting analysis of H_s . This restricted the review to 26 articles, which are listed in Tables 1, 2, and 3 (global, regional, local analysis respectively); these report the products employed (note that numerical models are here collectively referred as simulations), time periods covered by the data, and analysed wave statistics.

To facilitate the comprehension of the results, the MS is here grouped in the sub-basins shown in Fig. 3, namely: Alboran Sea (A_1S), Balearic Sea (BS), South-West MS (SW-MS), Gulf of Lion (GL), Ligurian Sea (L_iS), Tyrrhenian Sea (T_rS), Strait of Sicily (SS), Gulf of Sirte (GS), Ionian Sea (IS), Aegean Sea (A_eS), Adriatic Sea (A_dS), and Levantine Sea (L_eS). Note that, for the sake of simplicity, some of the basins were named after well known features they include, although they span wider areas (for example, the Gulf of Sirte extends to Egypt beyond the Lybian coastline).

We counted the number of articles detecting either positive or negative trends in each of the sub-basins. A preliminary analysis of the literature showed that, within some sub-basins, trends with opposite signs in different areas were identified; therefore, we split the analysis between upward and downward trends, extracting the respective ranges of variability and checking for the presence of significant ones. However, inferring the exact trends magnitude from the spatial maps provided in the literature is not trivial, especially when continuous color scales are used to show results. Besides, in case of blank areas, it is sometimes difficult to understand whether an article detected negligible trends or

Table 1 List of articles reviewed

Article	Data source	Lon/lat resolution	Period	H_s statistic
Gulev and Grigorjeva (2004)	VOS	$4^\circ \times 4^\circ$	1950–2008	Annual mean
Young et al. (2011)	Satellite	$2^\circ \times 2^\circ$	1985–2008	Monthly + annual mean, p90, p99
Young et al. (2012)	Satellite	$2^\circ \times 2^\circ$	1992–2008	H_s^{100}
Young and Ribal (2019)	Satellite	$2^\circ \times 2^\circ$	1985–2018	Monthly + annual mean, p90
Lin and Oey (2019)	Satellite	$1^\circ \times 1^\circ$	1993–2015	Monthly mean
Meucci et al. (2020)	Simulations	$110 \text{ km} \times 110 \text{ km}$ $166 \text{ km} \times 166 \text{ km}$	1901–2010	Monthly mean
Timmermans et al. (2020)	Satellite simulations	$2^\circ \times 2^\circ$ $0.5^\circ \times 0.5^\circ$	1992–2017	Seasonal mean
Cao et al. (2021)	Simulations	$0.5^\circ \times 0.5^\circ$ $1^\circ \times 1^\circ$	1999–2013	Annual mean
Sharmar et al. (2021)	Simulations	$0.25^\circ \times 0.25^\circ$ $0.7^\circ \times 0.7^\circ$ $0.312^\circ \times 0.312^\circ$ $0.625^\circ \times 0.5^\circ$	1980–2019	Annual mean, p95
Young and Ribal (2022)	Satellite	$2^\circ \times 2^\circ$	1985–2008	Monthly mean
Casas-Prat et al. (2022)	Simulations	$1^\circ \times 1^\circ$	1951–2010	Annual mean, max
Erikson et al. (2022)	Simulations	$0.5^\circ \times 0.5^\circ$	1980–2014	Seasonal p50, p90

Global scale analysis. Spatial resolution of the articles marked with the asterisk is in km (same in Tables 2 and 3)

Table 2 As in Table 1 for regional scale analysis

Article	Data source	Lon/lat resolution	Period	H_s statistic
Lionello and Sanna (2005)	Simulations	$25 \text{ km} \times 25 \text{ km}$	1958–2001	Monthly + seasonal mean
Ratsimandresy et al. (2008)	Simulations	$0.125^\circ \times 0.125^\circ$ $0.25^\circ \times 0.25^\circ$	1958–2001	Annual mean, p90
Musić and Nicković (2008)	Simulations	$0.5^\circ \times 0.5^\circ$ $0.125^\circ \times 0.125^\circ$	1958–2001	Annual p50, p90
Zacharioudaki et al. (2015)	Simulations	$0.1^\circ \times 0.1^\circ$	1960–2001	Annual + seasonal mean, p99
De Leo et al. (2020)	Simulations	$0.1273^\circ \times 0.09^\circ$	1979–2018	Annual mean, p98, maxima
De Leo et al. (2021a)	Simulations	$0.1273^\circ \times 0.09^\circ$	1979–2018	Annual maxima
Barbariol et al. (2021)	Simulations	$0.05^\circ \times 0.05^\circ$	1980–2019	Seasonal p50, p99
Amarouche et al. (2022)	Simulations	$0.033^\circ \times 0.033^\circ$	1979–2019	Annual + seasonal mean, maxima
Caloiero et al. (2022)	Simulations	$0.75^\circ \times 0.75^\circ$	1979–2018	Annual + seasonal mean, maxima
Elshinnawy and Antolínez (2023)	Simulations	$0.1^\circ \times 0.1^\circ$	1980–2019	Annual p50, p99.5

Table 3 As in Table 1 for local scale analysis

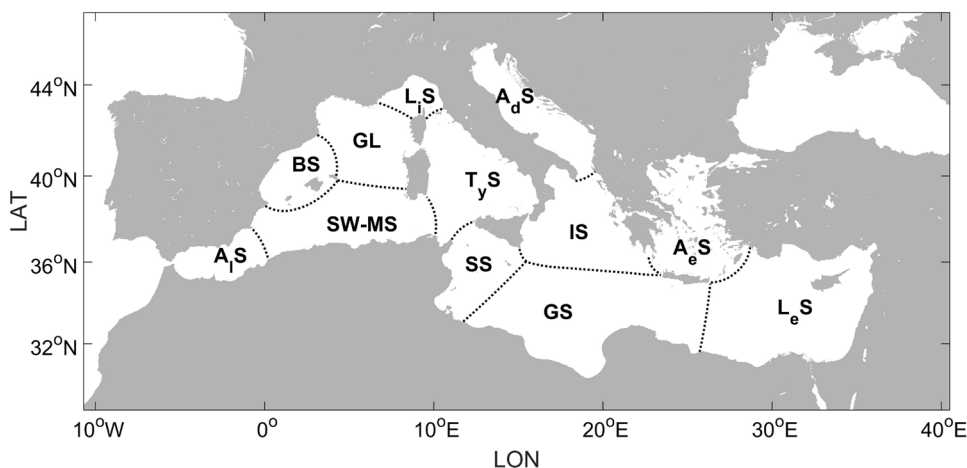
Article	Data source	Lon/lat resolution	Period	H_s statistic
Martucci et al. (2010)	Simulations	$0.25^\circ \times 0.25^\circ$	1958–1999	Annual, seasonal mean
Pomaro et al. (2017)	Observations	NA	1979–2015	Monthly mean
Caloiero et al. (2019)	Simulations	$O(10) \text{ km}$	1979–2017	Annual, seasonal mean
Lo Feudo et al. (2022)	Simulations	$0.5^\circ \times 0.5^\circ$	1950–2019	Annual, seasonal, monthly mean

No resolution is reported for Pomaro et al. (2017) as this work refers to a single site

the area was not covered by data (especially at low spatial resolution; see for example the trends in the Adriatic Sea resulting from Young and Ribal, 2019; Cao et al., 2021). For

this reason, in this review more attention is paid to trends sign and significance rather than the exact annual rates of change.

Fig. 3 Basins used to group trend estimates in the MS: Alboran Sea (A_1S in the figure); Balearic Sea (BS); South-West MS (SW-MS); Gulf of Lion (GL); Ligurian Sea (L_1S); Tyrrhenian Sea (T_yS); Strait of Sicily (SS); Gulf of Sirte (GS); Ionian Sea (IS); Adriatic Sea (A_dS); Aegean Sea (A_eS); Levantine Sea (L_eS)



To summarise H_s trends for each sub-basin, we pooled together all the findings on mean, median (p50), and modal H_s , deemed representative of *mean climate conditions*. On the other hand, results for percentiles higher than 90th and annual maxima H_s were considered jointly and referred to as *extreme sea states* (see Fig. 4; a similar approach is used by Ratsimandresy et al. 2008). Note that the i th percentile is henceforth shortened to p_i (e.g. the 90th percentile is indicated as p_{90}). We retained trends arising from both annual and monthly series; although the latter may be affected by seasonal periodicity, this is usually filtered out using appropriate metrics, such as seasonal-MK; in this respect, see e.g. Young and Ribal (2019), who claimed that trends of monthly series can be extended to annual statistics. As for trends on seasonal subsets, we only retained those computed for extreme sea states over winter months, as these are representative of yearly extremes in the MS. By contrast, trends on seasonal mean such as in Timmermans et al. (2020)

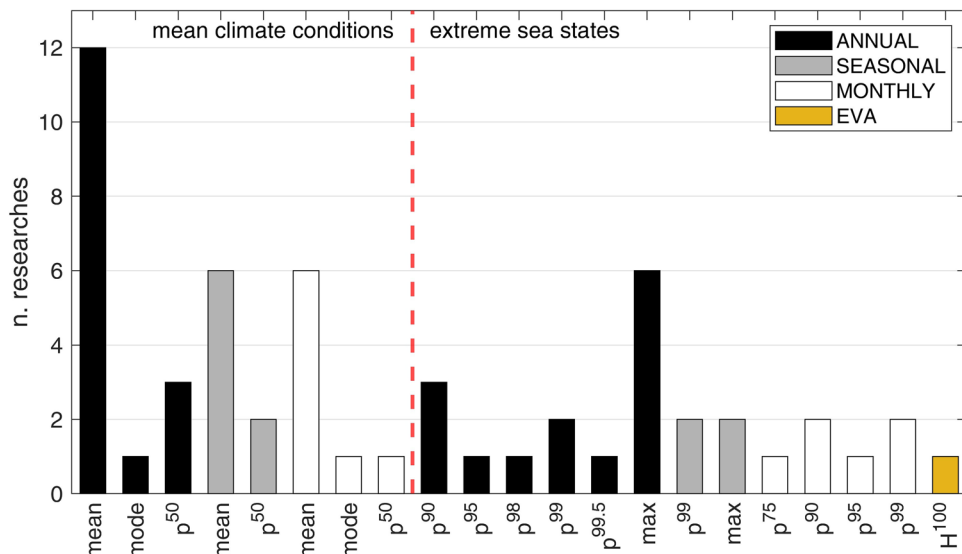
cannot be directly compared to annual statistics. In case of studies presenting analysis at both yearly and seasonal results (Zacharioudaki et al. 2015; Caloiero et al. 2022), we only considered the former. As for the significance of trends, we consider that a significant trend is present in a sub-basin if this is detected in any area regardless of its extension. While this approach may overestimate the number of articles finding trends at given basins, it allows for a quick assessment and to refine the analysis in hot-spots if needed.

3 Significant wave height trends

3.1 Global analysis

Studies examining global-scale trends employed VOS (Volunteer Observing Ships), satellite altimetry data, and numerical results with resolutions ranging from 0.25° to 4° in both

Fig. 4 Number of occurrences of H_s statistics employed for trend detection and quantification in the literature reviewed. Black, grey, and white bins denote annual, seasonal, and monthly statistics, respectively. H^{100} indicates 100 years return period wave (Young et al. 2012)



latitude and longitude, which corresponds to approximately 25 km to 400 km at the MS latitudes (see Table 1). Inevitably, this has an impact on the resolution of the results for the sub-basins. Besides, time-series related to nearby locations are often pooled together, potentially adding further uncertainty to the trend estimates.

For mean wave climates, widespread significant and positive trends over the whole MS were detected by Lin and Oey (2019) (with the exception of the Strait of Sicily), and Meucci et al. (2020) when using reanalysis products (while they found no trends when relying on a model-only integration). Also Gulev and Grigorieva (2004) found positive and significant trends based on VOS; however, their results may be biased since ships tend to avoid stormy conditions. By contrast, Young et al. (2011) mostly detected significant and negative trends over vast areas in the central MS, while no significant trends could be later identified by Young and Ribal (2019). Their results greatly diverge for mode and mean H_s series, suggesting that changes have occurred in the shapes of the wave height pdf's over the 33-year measurement period. No significant trends were neither found by Casas-Prat et al. (2022) nor by Cao et al. (2021); as for the latter, they only spotted positive and significant trends during the so called slow-down period (1999–2013) especially in the Ionian Sea. Such discrepancies call into question the reliability of trends found using short time series. In this respect, Sharmar et al. (2021) showed how to rely on different periods can result in opposite trends within the Northeast Pacific Ocean, Northeast Atlantic Ocean, and South Indian Ocean; they also found diverging results when comparing trends based on ERA products (which incorporates both wind speed and wave height measurements) and Climate Forecast System Reanalysis, CFSR (which only assimilates wind speed data). On the contrary, a high consensus in seasonal p50 and p90 trends estimates was pointed out by Erikson et al. (2022) based on a 7-members ensemble of global wave products by not considering CFSR data. The season analysed plays also a crucial role in trends assessment: for example, all data used in Timmermans et al. (2020) yield significant upward trends in the Gulf of Lion for January, February, and March, but none leads to significant-positive trends for June, August, and September. However, note that seasons at the MS latitudes are more commonly grouped in December, January, and February (winter)–March, April, and May (spring)–June, July, and August (summer)–September, October, and November (fall; e.g., Erikson et al. 2022) and an objective definition of season (e.g. Kotsias et al. 2021) is not always used in the reviewed literature.

In case of extreme wave climates, no significant trend patterns were highlighted by Young et al. (2011) and Sharmar et al. (2021), while Casas-Prat et al. (2022) found widespread and positive (negative) trends in the eastern (western)

MS, although not significant. By contrast, positive and significant trends characterize the western Mediterranean in Young and Ribal (2019). No significant trends can be appreciated in the MS for high return period waves: Young et al. (2012) assessed trends for 100 years H_s computed starting from 4-year long time slices, an interval too short to obtain reliable estimates; in fact, the computed variability due to trends is comparable to the confidence intervals of the return levels. Also Takbash and Young (2020) investigated trends in the 100 years H_s , but did not include the MS in their analysis.

3.2 Mediterranean basin analysis

In case of articles investigating trends at the regional and sub-basin scales, more detailed analysis can be often drawn thanks to higher spatial resolutions, which is found in the literature to range between 0.05° and 0.25° in studies using numerical hindcast. High-resolution numerical weather hindcasts can indeed reproduce small-scale structures even if these are not fully captured by large-scale forcing (Skamarock 2004), hence wave hindcast benefit from increased resolution in wind forcing. However, uncertainties may arise from the model physical calibration parameters, from boundary conditions in case sub-basins are numerically simulated, and/or propagate across different scales (Wilby and Dessai 2010) throughout the downscaling process (Shepherd et al. 2018). For example, Caloiero et al. (2019) downscaled hindcast data from deep waters to several coastal location around Calabria (South of Italy), and found trends not fully consistent to their offshore counterparts. As a matter of fact, wave propagation can be another step affecting trend estimates, prompting the need to carefully calibrate wave models for coastal environments (see in this respect De Leo et al. 2022). The above considerations can partly explain the divergences in trends results identified by studies using different model setups/products, as shown below.

For the mean wave climate, Caloiero et al. (2022) and Amarouche et al. (2022) highlighted positive and significant trends distributed over the whole MS and the western MS, respectively; on the contrary, Musić and Nicković (2008) mainly found negative trends in the western MS. Similar findings were presented by Zacharioudaki et al. (2015), De Leo et al. (2020), Barbariol et al. (2021), and Elshinnawy and Antolínez (2023), who highlighted negative and significant trends clustered in the Levantine Basin, with Elshinnawy and Antolínez (2023) showing positive and significant trends in the Alboran Sea only. Sub-basins and single locations within the MS were analysed in few works. Negative and significant trends were computed in the Adriatic, the Ionian, and the Tyrrhenian Seas by Martucci et al. (2010), while Pomaro et al. (2017) found positive trends in the North Adriatic Sea. Finally, Lo Feudo et al. (2022) analysed trends

in mean wave climate on annual, seasonal, and monthly time scales at a single site in front of Calabria coastline (South Tyrrhenian Sea) and could not find significant ones for H_s .

For the extreme sea states, results from De Leo et al. (2020), Amarouche et al. (2022) diverge from those by Caloiero et al. (2022), in particular for the annual maxima H_s south of the Gulf of Lion. Both De Leo et al. (2020) and Amarouche et al. (2022) found negative trends there, contrarily to Caloiero et al. (2020), whose results are consistent with those by Elshinnawy and Antolínez (2023). The aforementioned differences can be also explained by the different confidence levels used to detect trends through the MK, i.e., 5% (De Leo et al. 2020; Amarouche et al. 2022) and 10% (Caloiero et al. 2022; Elshinnawy and Antolínez 2023); and different statistics to characterise extreme and mean conditions (p99.5 and median rather than AM and mean in Elshinnawy and Antolínez 2023). Results by De Leo et al. (2020) were further confirmed by De Leo et al. (2021a), who assessed the rate of change of the location parameter (μ_t) of non-stationary Generalised Extreme Value distribution for annual maxima H_s . Interestingly, all the above mentioned researches found negative and significant trends in the Southern Tyrrhenian Sea. Zacharioudaki et al. (2015) highlighted widespread positive and significant trends west of the Crete Island (Greece) for annual p99 H_s series when taking 1960–1981 as a reference interval. The same analysis led to opposite trends for the 1981–2001 period, showing consistency issues discussed in Sect. 2; even more so, since trends showed a marked seasonal variability. Similar findings were pointed out by Barbariol et al. (2021); Amarouche et al. (2022); Caloiero et al. (2022); Elshinnawy and Antolínez (2023) who remarked that, in case of seasonal analysis, trends can change dramatically depending on the

months subset considered; in particular, trends computed for June–September subsets are milder, because of the low magnitude of sea states compared to extreme data, such as AM, that usually occur during winter time. Additional analysis were carried out by Caloiero et al. (2020) and Caloiero and Aristodemo (2021) based on the ERA-Interim dataset (Dee et al. 2011); however, further on in the article we only consider Caloiero et al. (2022), as this embeds the results of the previous works (in the latter work authors have extended the analysed area adopting the same data and the same methodology).

3.3 Consensus

Using the distinction between mean climate conditions and extreme sea states and the methodology explained in Sect. 2 we counted the negative and positive trends found for each sub-basin of the MS and distinguished between significant and not significant ones. Summary of the results are shown in Fig. 5 (mean wave climate) and Fig. 6 (extreme sea states). The number of researches either detecting trends (significant and not significant) or not finding any are normalised over the total number of research per each basin (such ratio is referred to as χ in the figures, with subscript – and + to indicate negative and positive trends respectively). Note that negative and positive trends can be detected in different parts of the same sub-basin, hence $\chi^+ + \chi^-$ can be larger than 1. In the figure NA indicates either that the significance was not assessed in the study considered or that no trends were identified.

Overall, for mean climate trends, works finding mean negative trends represent the majority for most basins (right side of Fig. 5). However, when significant trends only are

Fig. 5 Summary of the research investigating trends for mean wave climate. Left side: positive trends; right side: negative trends. The number of researches either detecting trends (significant and not significant) or not finding any are normalised over the total number of research per each basin (such ratio is referred to as χ in the figures)

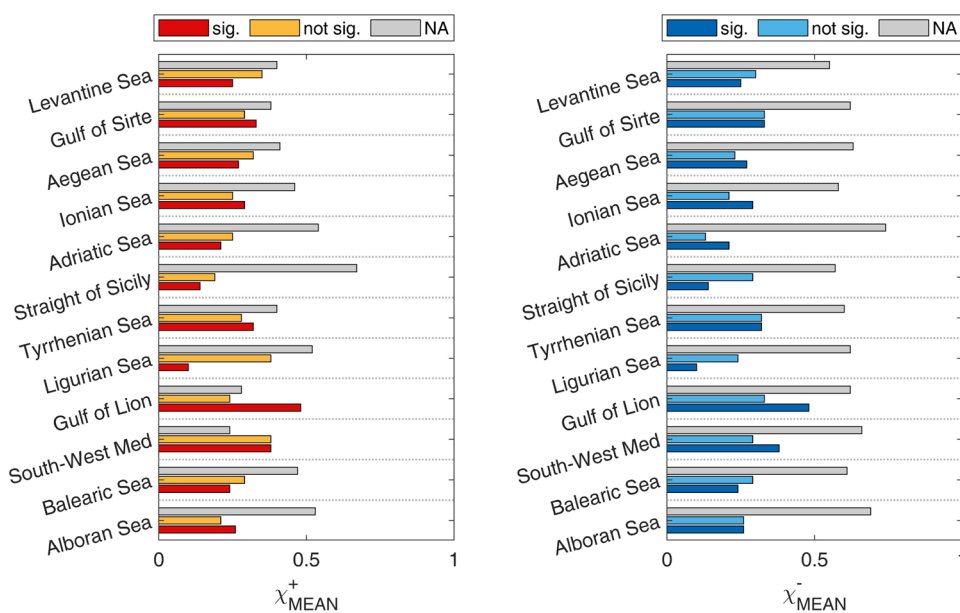
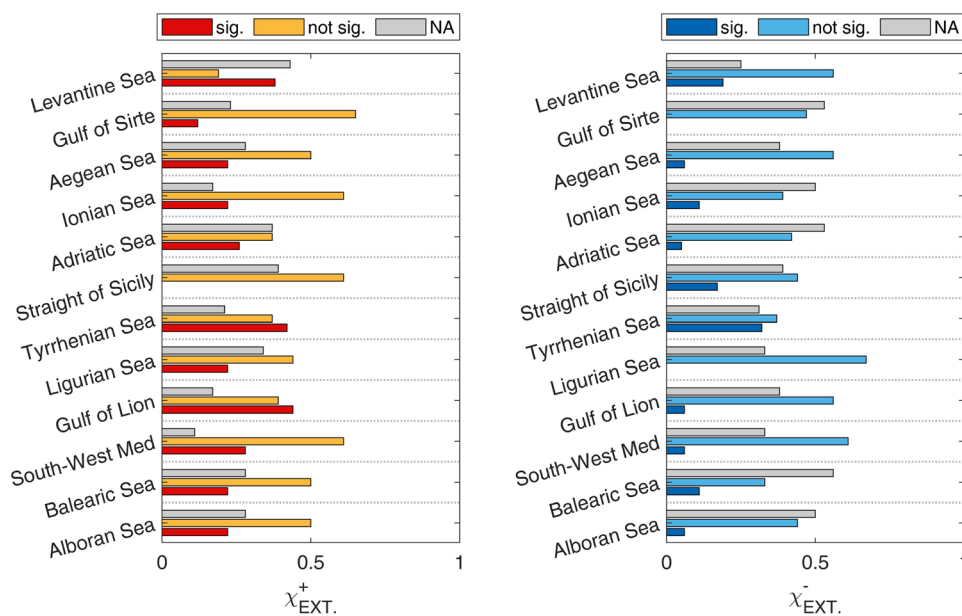


Fig. 6 Same as Fig. 5 for extreme sea states



considered, positive and negative trends are almost as frequent. Significant trends are detected predominantly in the western MS and in the Gulf of Sirte. In particular in the Gulf of Lion, and the South-West MS (left side of Fig. 5) positive significant trends are more abundant than non significant or unclassified trends. This is never the case for negative trends. In case of extreme sea states trends, there are many basins where, although some trends could be identified, these were mostly found to be unclassified or not statistically significant; such consideration holds for 10 out of 12 basins for positive trends, and for all basins in case of negative trends.

Looking at the significant trends, the Gulf of Lion is the basin most affected by upward significant trends, that are mostly located in the west part of this sub-basin. The Tyrrhenian Sea is also interested by positive and significant extreme sea states trends. This basin is also the one showing the largest amount of researches finding negative and significant trends. These trends coexist in the same sub-basin and show a clear north/south split, with negative trends located in the southern sub-basin (off the Calabria coast, Italy) and the positive in the northern part (towards the Ligurian Sea), respectively, (De Leo et al. 2020; De Leo et al. 2021a; Caloiero et al. 2022; Amarouche et al. 2022), therefore they should be further analysed.

The consensus on the relation between trends in sea states and long-term changes in weather patterns is also not general. Correlations between winter averaged H_s series and the North Atlantic Oscillation (NAO) and Scandinavian index have been investigated (Lionello and Sanna 2005; Barbariol et al. 2021), as well as links between wave climate variability and the Mediterranean Oscillation Index and the East Atlantic pattern (Elshinnawy and Antol3nez 2023; Izaguirre et al.

2010). However, inter-annual variability in wave climate can only partly be explained by teleconnections (Barbariol et al. 2021), since wave regimes are more closely related to local centers of action (Lionello and Sanna 2005) and local generated wind (Lin and Oey 2019; Cao et al. 2021), although this does not imply that wave trends mirror trends in wind climate (Alves 2006).

4 Other sea state parameters

For most coastal and off-shore projects and operations, H_s is the most relevant parameter. Hence, the vast majority of articles reviewed attempted to assess climatic trends by analysing time series of H_s data. However, other parameters can also play a crucial note; in particular, changes in waves direction of propagation θ can directly affect shoreline dynamics (Zacharioudaki and Reeve 2011; Casas-Prat and Sierra 2012; Chataigner et al. 2022) and harbour agitation (Casas-Prat and Sierra 2012; Sierra et al. 2017). Trends in θ need to be assessed independently, as this cannot be inferred from H_s , unlike the wave period, for which simplified parametric formulae can be employed, at least in case of extreme waves when the two parameters are almost linearly related (see e.g., Goda 2003; Callaghan et al. 2008). Moreover, estimation of trends in wave direction is a challenging task due to the intrinsic nature of the data to analyse: peak direction θ_p , for example, is a non-continuous quantity that depends strongly on the spectral grid resolution and hence could present different behaviour depending on the number of bins employed for partitioning the spectrum; mean direction θ_m , on the other hand, may not represent the real direction of propagation of wave storms, especially in an

enclosed sea such as the MS, where swell conditions are rare, while ocean waves and multiple wave systems occur frequently. For these reasons, to date, little research has been carried out on trends in time-series of θ in the MS. Time-series of storms belonging to different directional sectors can be characterised by opposite trends (Casas-Prat and Sierra 2010b), shedding light on a crucial aspect: CC may differently affect storms that propagate from different directions (results were further confirmed in Casas-Prat and Sierra 2010a, 2012). Sierra et al. (2017) and De Leo et al. (2021b) assessed trends in future wave projections and could not find relevant changes with respect to present conditions, while Erikson et al. (2022) highlighted mild counter clockwise trends in annual series of mean θ_m in the Levantine Basin. Trends in wave period are even less studied. To the best of our knowledge, wave periods at global scale were analysed only by Gao et al. (2021) and Erikson et al. (2022). However, previous works estimated trends in wave storminess, therefore coupling information about H_s with storms frequency and duration, which could dramatically affect wave climate trends (Casas-Prat and Sierra 2010b; Lira-Loarca et al. 2021b). In this respect, the analysis of trends in series of Total Storm Wave Energy (Arena et al. 2015) and Storm Power Index (Dolan and Davis 1992) carried out by Amarouche and Akpınar (2021) found patterns similar to H_s trends in the Tyrrhenian Sea; other hot spots were spotted in the Gulf of Lion (towards the Balearic Sea) and in the Alboran Sea. Such patterns were altered when computing trends on a decadal base (Amarouche et al. 2022). Finally, no significant trends in the yearly number of rough sea states were reported by Erikson et al. (2022).

5 Conclusions

This review analysed the results of peer reviewed articles researching historical ocean waves trends in the Mediterranean Sea (MS). Most of the studies focused on the significant wave height H_s trends, while other sea state parameters, notably wave direction and period appear to be under-studied in this context. Previous research indicated limited consensus across all levels of H_s analysed in the MS, neither for mean (Fig. 5) nor for extreme (Fig. 6) H_s . Negative mean wave climate trends are more frequently detected across the MS than positive ones. However, the western MS shows notable, statistically significant, positive trends. Similarly, for extreme sea state positive trends are detected in the western MS, in particular in the Gulf of Lion and the Tyrrhenian Sea, with complex spatial distribution. The western MS is, therefore, the only sub-basin in which positive historical trends are found for both mean wave climate and extreme values of H_s by a number of studies.

Some considerations should be provided on the links between historical trends and future projected trends, which have not been the focus of this review. However, given the importance of the use of projections in studies aimed at assessing climate scenarios, it is worth pointing out that, for the MS, historical trends and future projected trends diverge. Projections are obtained from future emissions scenarios, which differ from the past, therefore this difference is not surprising. The works by Sierra et al. (2017) off the island of Menorca, Benetazzo et al. (2012); Ruol et al. (2022) in the Adriatic Sea, De Leo et al. (2021b); Lira-Loarca et al. (2021a, 2021b); Simonetti and Cappiotti (2023) and Morim et al. (2021) at regional and global scales, respectively, all indicate a decrease in the magnitude of future wave climate within the MS.

The lack of consensus found in this review may be due to the sources of uncertainty that have been proven to affect trend estimates, such as data source (Timmermans et al. 2020), statistics employed to characterise mean or extreme conditions (Young and Ribal 2019), length of the time period used for the analysis (Zacharioudaki et al. 2015; Cao et al. 2021; Sharmar et al. 2021), and thresholds used to prove trends statistical significance (De Leo et al. 2020; Caloiero et al. 2022). Also, in addition to the effect of the different sources of data, within the same source, the varying spatial and time resolution used in various studies may contribute to the lack of a wider consensus on regional trends. This aspect has not been analysed in detail yet. Similarly, for studies using numerical models, the effect of increase of observations in assimilation, known to introduce spurious trends (Wohland et al. 2019; Meucci et al. 2020), is not always considered in the studies in which reanalysis is used. The availability of increasingly longer time series, such as the ERA5 database, may drive studies on the reconstruction of historical trends spanning longer periods, therefore the quantification of the effect of different data assimilated on trends should be considered as a priority.

Based on the above-mentioned aspects, it is clear that the current state of the art on the knowledge of historical trends in the MS, while providing useful insights, needs to improve the reliability of the results by an improved quantification of the uncertainty due to the data and models used. Additionally, also methods used to detect trends and their statistical significance should be improved, above all when multiple studies are compared. While linear trends represent a helpful and straightforward information, the variability of the modelling hypotheses and observations used can generate large variability among studies (Morim et al. 2019), as also observed in the studies reviewed here. Future research should mitigate this by, for example, using an approach similar to that used for projections, where local results are corrected for bias and averaged on individual grid points before determining a trend, (see

Lira-Loarca et al. 2023, and references therein), although this does not ensure to span the total uncertainty (Shepherd et al. 2018). Linear trends estimates based on time series at one location themselves should be thoroughly validated by e.g., using multiple tests and possibly analysing the sensitivity to the reference time period and data employed.

A further area in which research is needed is the establishment of links between sea state trends and weather patterns, in which, as discussed in Sect. 3.3, a wide consensus is not present. In this aspect it is needed to understand the role of indexes interpreting weather processes at scales larger than the MS, and changes in local ones. However, this analysis is complicated by the lack of consensus on the significant trends. As noted throughout this review, available studies mainly focus on H_s trends, with other sea states parameter being understudied. In addition the spatial coherence of the trends within sub-basins has not yet been assessed. For the former aspect, an alternative to analyse spectral periods, is potentially the analysis of full spectra, which has been shown to allow for more robust analysis than the integrated wave parameters, see Lira-Loarca and Besio (2022). For the latter aspect, it is crucial to understand the actual spatial coherence of trends, as done in the field of sea level trends analysis (Calafat et al. 2022).

6 Supplementary information

The list of articles reviewed with their bibliographical information and type of analysis (global, regional, or local) is provided as supplementary spreadsheet file.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00382-023-06984-4>.

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Data availability The datasets analysed in this review article are not generated within this study. Data used to generate the figures and tables, which result from the analysis of the available literature, are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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References

- Abraham JP, Baringer M, Bindoff NL et al (2013) A review of global ocean temperature observations: implications for ocean heat content estimates and climate change. *Rev Geophys* 51(3):450–483
- Alexandrakis G, Manasakis C, Kampanis NA (2015) Valuating the effects of beach erosion to tourism revenue. A management perspective. *Ocean Coast Manag* 111:1–11
- Alves JHG (2006) Numerical modeling of ocean swell contributions to the global wind-wave climate. *Ocean Model* 11(1–2):98–122
- Amarouche K, Akpınar A (2021) Increasing trend on storm wave intensity in the western Mediterranean. *Climate* 9(1):11
- Amarouche K, Akpınar A, Semedo A (2022) Wave storm events in the Western Mediterranean Sea over four decades. *Ocean Model* 170:101933
- Amarouche K, Bingölbali B, Akpınar A (2022) New wind-wave climate records in the Western Mediterranean Sea. *Clim Dyn* 58(5):1899–1922
- Arena F, Laface V, Malara G et al (2015) Estimation of downtime and of missed energy associated with a wave energy converter by the equivalent power storm model. *Energies* 8(10):11575–11591
- Barbariol F, Davison S, Falcieri FM et al (2021) Wind waves in the Mediterranean Sea: an ERA5 reanalysis wind-based climatology. *Front Mar Sci* 8:760614
- Benetazzo A, Fedele F, Carniel S et al (2012) Wave climate of the Adriatic Sea: a future scenario simulation. *Nat Hazard* 12(6):2065–2076
- Besio G, Briganti R, Romano A et al (2017) Time clustering of wave storms in the Mediterranean Sea. *Nat Hazard* 17(3):505–514
- Calafat FM, Wahl T, Tadesse MG et al (2022) Trends in Europe storm surge extremes match the rate of sea-level rise. *Nature* 603(7903):841–845
- Callaghan D, Nielsen P, Short A et al (2008) Statistical simulation of wave climate and extreme beach erosion. *Coast Eng* 55(5):375–390
- Caloiero T, Aristodemo F (2021) Trend detection of wave parameters along the Italian Seas. *Water* 13(12):1634
- Caloiero T, Aristodemo F, Algieri Ferraro D (2019) Trend analysis of significant wave height and energy period in southern Italy. *Theoret Appl Climatol* 138:917–930
- Caloiero T, Aristodemo F, Ferraro DA (2020) Changes of significant wave height, energy period and wave power in Italy in the period 1979–2018. *Environ Sci Proc* 2(1):3
- Caloiero T, Aristodemo F, Ferraro DA (2022) Annual and seasonal trend detection of significant wave height, energy period and wave power in the Mediterranean Sea. *Ocean Eng* 243:110322
- Cao Y, Dong C, Young IR et al (2021) Global wave height slowdown trend during a recent global warming slowdown. *Remote Sens* 13(20):4096

- Casas-Prat M, Sierra J (2010a) Trend analysis of the wave storminess: the wave direction. *Adv Geosci* 26:89–92
- Casas-Prat M, Sierra J (2010b) Trend analysis of wave storminess: wave direction and its impact on harbour agitation. *Nat Hazard* 10(11):2327–2340
- Casas-Prat M, Sierra J (2012) Trend analysis of wave direction and associated impacts on the Catalan coast. *Clim Change* 115(3):667–691
- Casas-Prat M, Wang XL, Mori N et al (2022) Effects of internal climate variability on historical ocean wave height trend assessment. *Front Mar Sci* 9:847017
- Chataigner T, Yates M, Le Dantec N et al (2022) Sensitivity of a one-line longshore shoreline change model to the mean wave direction. *Coast Eng* 172:104025
- Chen X, Zhang X, Church JA et al (2017) The increasing rate of global mean sea-level rise during 1993–2014. *Nat Clim Chang* 7(7):492–495
- Dangendorf S, Marcos M, Wöppelmann G et al (2017) Reassessment of 20th century global mean sea level rise. *Proc Natl Acad Sci* 114(23):5946–5951
- De Leo F, De Leo A, Besio G et al (2020) Detection and quantification of trends in time series of significant wave heights: an application in the Mediterranean Sea. *Ocean Eng* 202:107155
- De Leo F, Besio G, Briganti R et al (2021a) Non-stationary extreme value analysis of sea states based on linear trends. Analysis of annual maxima series of significant wave height and peak period in the Mediterranean Sea. *Coast Eng* 167:103896
- De Leo F, Besio G, Mentaschi L (2021b) Trends and variability of ocean waves under RCP8.5 emission scenario in the Mediterranean Sea. *Ocean Dyn* 71(1):97–117
- De Leo F, Enríquez AR, Orfila A et al (2022) Uncertainty assessment of significant wave height return levels downscaling for coastal application. *Appl Ocean Res* 127:103303
- Dee DP, Uppala SM, Simmons AJ et al (2011) The era-interim reanalysis: configuration and performance of the data assimilation system. *Q J R Meteorol Soc* 137(656):553–597
- Dolan R, Davis RE (1992) An intensity scale for Atlantic coast northeast storms. *J Coast Res* 1992:840–853
- Durack PJ, Wijffels SE, Matear RJ (2012) Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science* 336(6080):455–458
- Elshinnawy AI, Antolínez JA (2023) A changing wave climate in the Mediterranean Sea during 58-years using UERRA-MESCAN-SURFEX high-resolution wind fields. *Ocean Eng* 271:113689
- Enríquez AR, Marcos M, Álvarez-Ellacuría A et al (2017) Changes in beach shoreline due to sea level rise and waves under climate change scenarios: application to the balearic islands (western mediterranean). *Nat Hazard* 17(7):1075–1089
- Erikson L, Morim J, Hemer M et al (2022) Global ocean wave fields show consistent regional trends between 1980 and 2014 in a multi-product ensemble. *Commun Earth Environ* 3(1):320
- Gao H, Liang B, Shao Z (2021) A global climate analysis of wave parameters with a focus on wave period from 1979 to 2018. *Appl Ocean Res* 111:102652
- Goda Y (2003) Revisiting Wilson's formulas for simplified wind-wave prediction. *J Waterw Port Coast Ocean Eng* 129(2):93–95
- Gulev SK, Grigorieva V (2004) Last century changes in ocean wind wave height from global visual wave data. *Geophys Res Lett* 31(24):1
- Hayashi Y (1982) Confidence intervals of a climatic signal. *J Atmos Sci* 39(9):1895–1905
- Helm KP, Bindoff NL, Church JA (2010) Changes in the global hydrological-cycle inferred from ocean salinity. *Geophys Res Lett* 37(18):1
- Hirsch RM, Slack JR, Smith RA (1982) Techniques of trend analysis for monthly water quality data. *Water Resour Res* 18(1):107–121
- Izaguirre C, Mendez FJ, Menendez M et al (2010) Extreme wave climate variability in southern Europe using satellite data. *J Geophys Res Oceans* 115(C4):1
- Kendall MG (1948) Rank correlation methods. Springer, London
- Kotsias G, Lolis CJ, Hatzianastassiou N et al (2021) An objective definition of seasons for the mediterranean region. *Int J Climatol* 41(S1):E1889–E1905
- Lin Y, Oey L (2019) Global trends of sea surface gravity wave, wind, and coastal wave setup. *J Clim* 33(3):769–785
- Lionello P, Sanna A (2005) Mediterranean wave climate variability and its links with NAO and Indian Monsoon. *Clim Dyn* 25(6):611–623
- Lira-Loarca A, Besio G (2022) Future changes and seasonal variability of the directional wave spectra in the Mediterranean Sea for the 21st century. *Environ Res Lett* 17(10):104015
- Lira-Loarca A, Cobos M, Besio G et al (2021a) Projected wave climate temporal variability due to climate change. *Stoch Env Res Risk Assess* 35(9):1741–1757
- Lira-Loarca A, Ferrari F, Mazzino A et al (2021b) Future wind and wave energy resources and exploitability in the Mediterranean Sea by 2100. *Appl Energy* 302:117492
- Lira Loarca A, Berg P, Baquerizo A et al (2023) On the role of wave climate temporal variability in bias correction of GCM–RCM wave simulations. *Climate Dyn* 2023:1–28
- Lo Feudo T, Mel RA, Sinopoli S et al (2022) Wave climate and trends for the marine experimental station of Capo Tirone based on a 70-year-long hindcast dataset. *Water* 14(2):163
- Mann HB (1945) Nonparametric tests against trend. *Econ J Econ Soc* 1945:245–259
- Martucci G, Carniel S, Chiggiato J et al (2010) Statistical trend analysis and extreme distribution of significant wave height from 1958 to 1999—an application to the Italian Seas. *Ocean Sci* 6(2):525–538
- Mattiazzo G (2019) State of the art and perspectives of wave energy in the Mediterranean Sea: backstage of ISWEC. *Front Energy Res* 7:114
- Mayer L, Jakobsson M, Allen G et al (2018) The Nippon Foundation-GEBCO seabed 2030 project: the quest to see the world's oceans completely mapped by 2030. *Geosciences* 8(2):63
- Meredith MP, King JC (2005) Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophys Res Lett* 32(19):1
- Meucci A, Young IR, Aarnes OJ et al (2020) Comparison of wind speed and wave height trends from twentieth-century models and satellite altimeters. *J Clim* 33(2):611–624
- Milne GA, Gehrels WR, Hughes CW et al (2009) Identifying the causes of sea-level change. *Nat Geosci* 2(7):471–478
- Morim J, Hemer M, Wang XL et al (2019) Robustness and uncertainties in global multivariate wind-wave climate projections. *Nat Clim Chang* 9(9):711–718
- Morim J, Vitousek S, Hemer M et al (2021) Global-scale changes to extreme ocean wave events due to anthropogenic warming. *Environ Res Lett* 16(7):074056
- Munday PL, Jones GP, Pratchett MS et al (2008) Climate change and the future for coral reef fishes. *Fish Fish* 9(3):261–285
- Musić S, Nicković S (2008) 44-year wave hindcast for the Eastern Mediterranean. *Coast Eng* 55(11):872–880
- Pomaro A, Cavaleri L, Lionello P (2017) Climatology and trends of the Adriatic Sea wind waves: analysis of a 37-year long instrumental data set. *Int J Climatol* 37(12):4237–4250
- Ratsimandresy A, Sotillo M, Albiach JC et al (2008) A 44-year high-resolution ocean and atmospheric hindcast for the Mediterranean Basin developed within the HIPOCAS project. *Coast Eng* 55(11):827–842
- Ruol P, Martinelli L, Favaretto C et al (2022) Representative and morphological waves along the Adriatic Italian coast in a changing climate. *Water* 14(17):2678

- Sánchez-Arcilla A, Sierra JP, Brown S et al (2016) A review of potential physical impacts on harbours in the Mediterranean Sea under climate change. *Reg Environ Change* 16:2471–2484
- Satta A, Puddu M, Venturini S et al (2017) Assessment of coastal risks to climate change related impacts at the regional scale: the case of the Mediterranean region. *Int J Disaster Risk Reduct* 24:284–296
- Scavia D, Field JC, Boesch DF et al (2002) Climate change impacts on US coastal and marine ecosystems. *Estuaries* 25:149–164
- Şen Z (2012) Innovative trend analysis methodology. *J Hydrol Eng* 17(9):1042–1046
- Serinaldi F, Chebana F, Kilsby CG (2020) Dissecting innovative trend analysis. *Stoch Env Res Risk Assess* 34:733–754
- Sharmar V, Markina MY, Gulev S (2021) Global ocean wind-wave model hindcasts forced by different reanalyses: a comparative assessment. *J Geophys Res Oceans* 126(1):e2020JC016710
- Shepherd TG, Boyd E, Calel RA et al (2018) Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Clim Change* 151:555–571
- Sierra J, Casas-Prat M, Campins E (2017) Impact of climate change on wave energy resource: the case of Menorca (Spain). *Renew Energy* 101:275–285
- Simeone S, Palombo L, Molinaroli E et al (2021) Shoreline response to wave forcing and sea level rise along a geomorphological complex coastline (Western Sardinia, Mediterranean Sea). *Appl Sci* 11(9):4009
- Simonetti I, Cappietti L (2023) Mediterranean coastal wave-climate long-term trend in climate change scenarios and effects on the optimal sizing of OWC wave energy converters. *Coast Eng* 179:104247
- Skamarock WC (2004) Evaluating mesoscale NWP models using kinetic energy spectra. *Mon Weather Rev* 132(12):3019–3032
- Takbash A, Young IR (2020) Long-term and seasonal trends in global wave height extremes derived from era-5 reanalysis data. *J Mar Sci Eng* 8(12):1015
- Theil H (1992) A rank-invariant method of linear and polynomial regression analysis. In: Henri Theil's contributions to economics and econometrics. Springer, London, pp 345–381
- Timmermans B, Gommenginger C, Dodet G et al (2020) Global wave height trends and variability from new multimission satellite altimeter products, reanalyses, and wave buoys. *Geophys Res Lett* 47(9):e2019GL086880
- Toggweiler JR, Russell J (2008) Ocean circulation in a warming climate. *Nature* 451(7176):286–288
- Toimil A, Camus P, Losada I et al (2020) Climate change-driven coastal erosion modelling in temperate sandy beaches: methods and uncertainty treatment. *Earth Sci Rev* 202:103110
- Watson CS, White NJ, Church JA et al (2015) Unabated global mean sea-level rise over the satellite altimeter era. *Nat Clim Chang* 5(6):565–568
- Wijffels S, Roemmich D, Monselesan D et al (2016) Ocean temperatures chronicle the ongoing warming of Earth. *Nat Clim Chang* 6(2):116–118
- Wilby RL, Dessai S (2010) Robust adaptation to climate change. *Weather* 65:180–185
- Winton M, Griffies SM, Samuels BL et al (2013) Connecting changing ocean circulation with changing climate. *J Clim* 26(7):2268–2278
- Wohland J, Omrani NE, Witthaut D et al (2019) Inconsistent wind speed trends in current twentieth century reanalyses. *J Geophys Res Atmos* 124(4):1931–1940
- Young IR, Ribal A (2019) Multiplatform evaluation of global trends in wind speed and wave height. *Science* 364(6440):548–552
- Young IR, Ribal A (2022) Can multi-mission altimeter datasets accurately measure long-term trends in wave height? *Remote Sens* 14(4):974
- Young I, Zieger S, Babanin AV (2011) Global trends in wind speed and wave height. *Science* 332(6028):451–455
- Young I, Vinoth J, Zieger S et al (2012) Investigation of trends in extreme value wave height and wind speed. *J Geophys Res Oceans* 117(C11):1
- Zacharioudaki A, Reeve DE (2011) Shoreline evolution under climate change wave scenarios. *Clim Change* 108(1–2):73–105
- Zacharioudaki A, Korres G, Perivoliotis L (2015) Wave climate of the hellenic seas obtained from a wave hindcast for the period 1960–2001. *Ocean Dyn* 65(6):795–816

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