

Changes of Significant Wave Height, Energy Period and Wave Power in Italy in the Period 1979–2018 [†]

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[†] Presented at the 4th EWaS International Conference: Valuing the Water, Carbon, Ecological Footprints of Human Activities, Online, 24–27 June 2020.

Published: 7 August 2020

Abstract: An analysis of a 40-year long wave time series was performed, along the coasts of Italy, in order to identify ongoing trends of two synthetic parameters, significant wave height (H_s) and energy period (T_e), and of the wave power (P). First, wave data were deduced from the global atmospheric reanalysis ERA-INTERIM by the ECMWF and checked to verify their consistency. Then, a trend analysis was performed on mean values evaluated at annual and seasonal scales through the non-parametric Mann–Kendall test for three different significance levels equal to 90%, 95% and 99%. The obtained results could be useful for analyses linked to beach morphodynamics and on the identification of field installations of Wave Energy Converters (WECs).

Keywords: trend analysis; significant wave height; energy period; wave power; statistical tests

1. Introduction

Nowadays, the average population density in coastal areas is about twice the world's average, and the number of buildings and facilities close to the coastline is still increasing. For instance, eight of the world's top ten biggest cities are located by the coast. Coastal areas are thus stressed by human activities, and the impacts of climate change, such as variations in sea level, wave conditions and storm surges, are expected to worsen the problems coastal areas are already facing [1]. The effects of climate change on coastal areas can be analyzed considering long-term records of sea states. However, these data are scarce if compared with large datasets of land variables, e.g., rainfall and temperature, regularly collected since the beginning of the past century. However, wave climate variability and trends have been largely studied worldwide (e.g., [2]). For example, Aarnes et al. [3] investigated the significant wave height trend at annual and monthly scales for the period 1979–2012 and for the entire world. The results of this study evidenced a positive trend in mean wave conditions in the tropical ocean areas, and no trend or a slightly negative trend in the northern parts of the Pacific and Atlantic Oceans. A statistical analysis of sea states in two sub-periods, 1960–1999 and 1958–2001, has been performed in the Mediterranean basin considering the wave model WAM based on the ERA-40 dataset [4]. As a result, a clear negative trend in significant wave height during the first three decades and a positive trend in the last decade have been detected. With regard to Italy, significant wave height trends in the northern Adriatic Sea have been analyzed by Pomaro et al. [5] in the period 1979–2015, evidencing a clear reduction of the highest percentile (99th) and a smaller growth of the 50th and 75th ones. In southern Italy (Calabria region) Caloiero et al. [6] identified positive trends in two synthetic parameters, i.e., significant wave height and energy period.

Within this context, in this paper a trend analysis of the annual and seasonal mean values of two synthetic parameters, significant wave height and energy period, and of the wave power has been here carried out for the Italian coasts through the application of the Mann–Kendall non-parametric test.

2. Interest Zone and Input Wave Data

Italy is located in Southern Europe between latitudes 35° and 47° N, and longitudes 6° and 19° E. To the north, Italy borders France, Switzerland, Austria and Slovenia, and is roughly delimited by the Alpine watershed. To the south, it consists of the entirety of the Italian Peninsula and the two Mediterranean islands of Sicily and Sardinia, in addition to many smaller islands. Including the islands, Italy has a coastline length of about 7600 km. The Italian Seas are part of the Mediterranean Sea and, in particular, four different seas surround the Italian Peninsula: the Adriatic Sea in the east, the Ionian Sea in the south, and the Ligurian Sea and the Tyrrhenian Sea in the west. The maximum depth of the Italian seas exceeds 5000 m (in the Ionian Sea).

With reference to wave climate in the Italian Seas, the most energetic area is located off the western coast of Sardinia, with a yearly average wave power per unit crest length of about 12 kW/m. Moreover, the Sicilian channel, located off the northwestern and southern Sicilian coasts, highlights a yearly average wave energy flux per unit crest length that reaches 9 kW/m [7,8]. On the other hand, the Adriatic Sea, where the average wave power does not exceed 3 kW/m, is one of the least productive areas in Italy in terms of wave power. Similar values are observed in various zones of the Ionian and Tyrrhenian Seas and near the strait of Messina (e.g., [9]). A strong variability was observed off the Italian coasts on monthly basis for wave parameters, which resulted in relevant oscillations on a seasonal scale (e.g., [10]).

In this work, the wave data related to the significant wave height, H_s , and the energy period, T_e , in the period 1979–2018 were obtained from the global atmospheric reanalysis ERA-INTERIM by the European Center for Medium-Range Weather Forecasts (ECMWF), for a total of 40 years, a spatial resolution of $0.75^\circ \times 0.75^\circ$ and time sampling of 6 h.

3. Methodology

3.1. Analysis of Wave Nodes

The wave parameters representing sea states adopted in the present analysis are H_s and T_e . Moreover, the wave power per unit crest length, P , depending on H_s and T_e , is also considered.

Adopting the spectral analysis, the value of H_s is equal to:

$$H_s = 4\sqrt{m_0} , \quad (1)$$

where m_0 represents the zero-th spectral moment that is calculated as:

$$m_0 = \sum_{ij} S_{ij} \Delta f_i \Delta \theta_j , \quad (2)$$

where S_{ij} is the density over the i -th frequency and j -th direction, Δf_i is the i -th frequency width of the density and $\Delta \theta_j$ is the j -th angular width of the density.

The value of T_e , whose meaning is given by the variance-weighted mean period of the one-dimensional density spectrum, is determined by the following relationship:

$$T_e = \frac{m_{-1}}{m_0} , \quad (3)$$

where m_{-1} is the minus-one spectral moment given by:

$$m_{-1} = \sum_{ij} f_i^{-1} S_{ij} \Delta f_i \Delta \theta_j , \quad (4)$$

where f_i is the i -th frequency.

The wave power, P , is calculated by the following general expression valid for all water conditions (i.e., from deep to shallow):

$$P = Ec_g, \quad (5)$$

where E is the wave energy equal to:

$$E = \frac{\rho g}{16} H_s^2, \quad (6)$$

where ρ (water density) = 1025 kg/m³ and g (gravity acceleration) = 9.806 m/s². The group celerity, c_g , is expressed as:

$$c_g = \frac{c}{2} \left[1 + \frac{2kd}{\sinh(2kd)} \right], \quad (7)$$

where c (mean celerity) = L_m/T_e , k (mean wave number) = $2\pi/L_m$, d is the water depth and L_m is the mean wave length calculated through the linear dispersion as:

$$L_m = \frac{gT_e^2}{2\pi} \tanh(kd). \quad (8)$$

The values of H_s and T_e , taken from the ECMWF dataset, were subject to a processing phase in order to check their consistency for the subsequent analyses. Some criteria were adopted to eliminate non-physical i -th wave parameters in the following manner [11]:

- appearing as Not a Numbers, zero and repeated values;
- outlier data incompatible with their spatial location;
- $H_{s,i+1} - H_{s,i} > 1.5$ m;
- $T_{p,i}/T_{e,i} > 2$, where T_p is the peak period;
- $H_{s,i}/T_{p,i}^2 < 0.1g/(2\pi)$ (e.g., [12]).

3.2. Mann–Kendall Test

In order to determine the possible existence of temporal tendencies in the H_s , T_e and P values, the well-known Mann–Kendall (MK) non-parametric test has been applied [13,14].

For a series with dimension n , the MK statistic is obtained as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i); \quad \text{with} \quad \text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases}, \quad (9)$$

where x_j and x_i are the data values at times j and i , with $j > i$.

If x_i are independent and randomly ordered, for $n > 10$, the statistic S follows a normal distribution with zero mean and variance given by:

$$\text{Var}(S) = \frac{\left[n(n-1)(2n+5) - \sum_{i=1}^n t_i i(i-1)(2i+5) \right]}{18}, \quad (10)$$

with t_i number of ties of extend i .

Finally, the standardized test statistic Z_{MK} is computed as:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{for } S < 0 \end{cases}, \quad (11)$$

Using a two-tailed test for a specified significance level α , the null hypothesis is rejected if $|Z_{MK}|$ is greater than $Z_{1-\alpha/2}$ and the trend can be considered significant.

3. Results

In this section, the results of the trend analysis applied to the mean yearly and seasonal series of H_s , T_e and P off the Italian coasts are analyzed. Concerning the mean annual values of H_s , Figure 1 shows the results obtained by the application of the Mann–Kendall test. A relevant number of positive trends for H_s with a significance level of 99% can be noted. These values are located in the Tyrrhenian and Ionian Seas, close to the islands of Sardinia and Sicily and in the northern zone of the Adriatic Sea. Positive trends with a lower significance level (i.e., 90% and 95%) have been observed in the central and southern parts of the Adriatic Sea, and between Sardinia and the Ligurian Sea. Null trends have been detected for two nodes close the Ligurian Sea. With regard to T_e , positive trends with a significance level of 99% have been detected in all the areas of the Italian Seas (Figure 1). Regarding the last wave parameter involved, i.e., P , which depends on H_s and T_e , the trend analysis shows a significant variability off the Italian coasts (Figure 1). Indeed, positive trends with a significance level of 99% can be substantially noted in the Ionian Sea, in the northern zones of the Tyrrhenian and Adriatic Seas and in the southern part of Sardinia. Positive trends with significance levels of 90% and 95% refer to some parts of the central and southern areas of the Adriatic Sea, the majority of the Tyrrhenian Sea and close to the islands of Sicily and Sardinia. Null trends of P have been detected near the Ligurian Sea and along the Adriatic Sea.

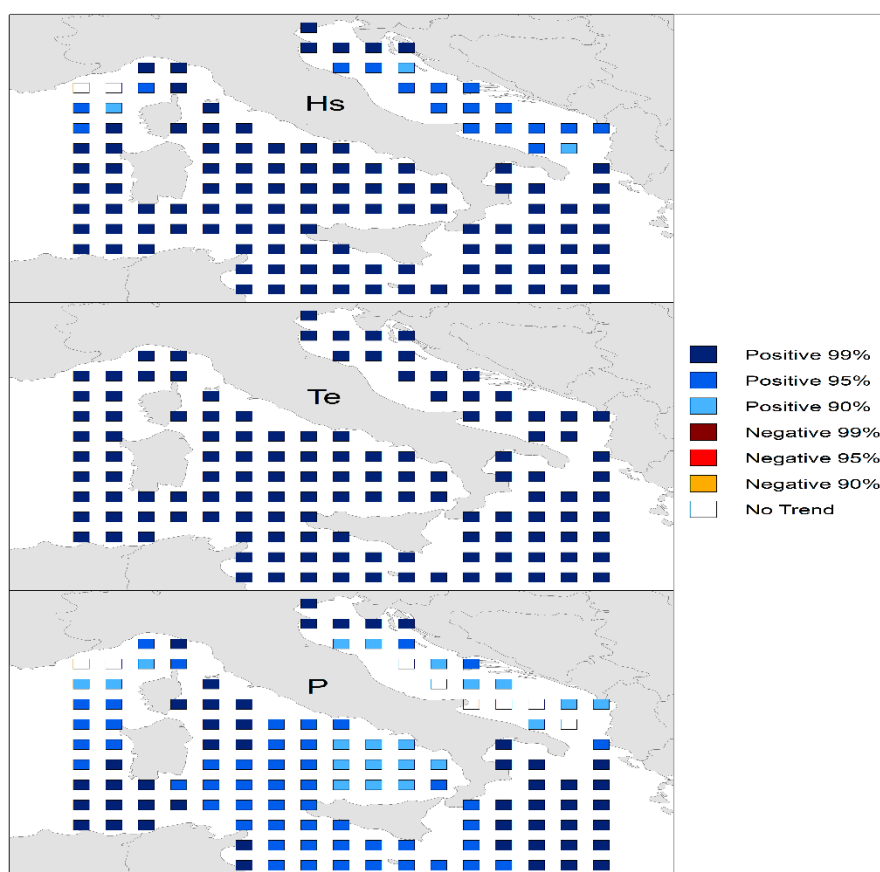


Figure 1. Spatial distribution of the annual trend of the mean values of the involved wave parameters off the Italian coasts.

On the basis of the application of the Mann–Kendall test, Figure 2 describes the spatial distribution of the mean seasonal trend of H_s in the Italian Seas. First, considerable variability in the four seasons can be observed. In winter (Figure 2), positive trends for H_s reach a maximum

significance level of 95%, detected for few nodes located in the Adriatic, Ionian and Tyrrhenian Seas and close to the southern part of Sardinia. Instead, more diffused nodes with trends have a significance level of 90%. No trends have been observed in the Ligurian Sea, in the southern zone of the Tyrrhenian and Ionian Seas, close to Sicily or along the Adriatic Sea. During spring (Figure 2), positive trends of H_s with a significance level of 99% are principally concentrated in the whole of the Ionian Sea, in the northern area of the Tyrrhenian Sea and between Sardinia and Sicily. The majority of the wave nodes in spring have a positive trend with a significance level of 95%. In particular, they are placed in the central and southern parts of the Tyrrhenian Sea, in the southern area of the Adriatic Sea and near Sicily. No trends have been observed near the Ligurian Sea or the northern part of the Adriatic Sea. Regarding summer (Figure 2), positive trends of H_s with a significance level of 99% have been substantially detected in the Ionian Sea and in some nodes of the Tyrrhenian and Adriatic Seas. Positive trends with a lower significance level have been mainly detected in the other areas of the Italian Seas. In this season, null trends have been observed close the Strait of Sicily. During autumn (Figure 2), the majority of the wave nodes show positive trends for H_s , with a significance level of 99%, in particular in the Ionian and Tyrrhenian Seas. Positive trends with lower significance levels have been detected close to Sicily and Sardinia and along the Adriatic Sea. No trends occur near the Ligurian Sea and in the southern part of the Adriatic Sea.

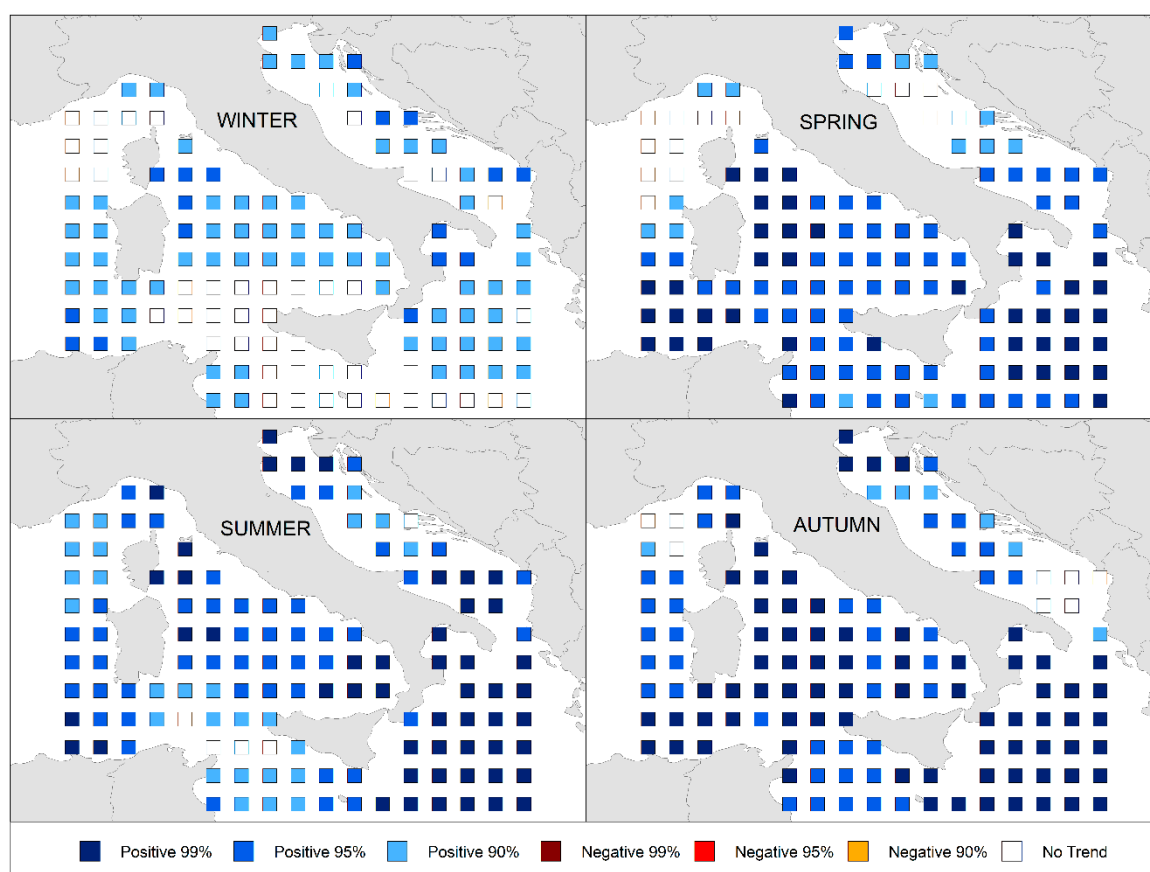


Figure 2. Spatial distribution of the seasonal trend of the mean values of H_s off the Italian coasts.

Figure 3 highlights the spatial distribution of the seasonal trend of the mean values of T_e in the Italian Seas. Compared to H_s , a different feature regarding the magnitude of the positive trends for the involved wave parameter is evident. Indeed, most of the wave nodes show marked positive trends for T_e , with a maximum significance level equal to 99% in every season. This is particularly clear during spring (Figure 3) and autumn (Figure 3). Additionally, the remaining nodes highlight a positive seasonal trend with a significance level of 95%. During winter (Figure 3), positive trends for T_e with a significance level of 95% appear in the southern part of the Ionian Sea and close to Sardinia and Sicily. In spring (Figure 3), just one wave node located in the Adriatic Sea shows a positive trend

with a significance level of 95%. During summer (Figure 3), these trends have been detected only in the northern area of the Tyrrhenian Sea and in the western part of Sardinia. With regard to autumn (Figure 3), few nodes with positive trends with a significance level of 95% have been observed in the southern part of the Adriatic Sea.

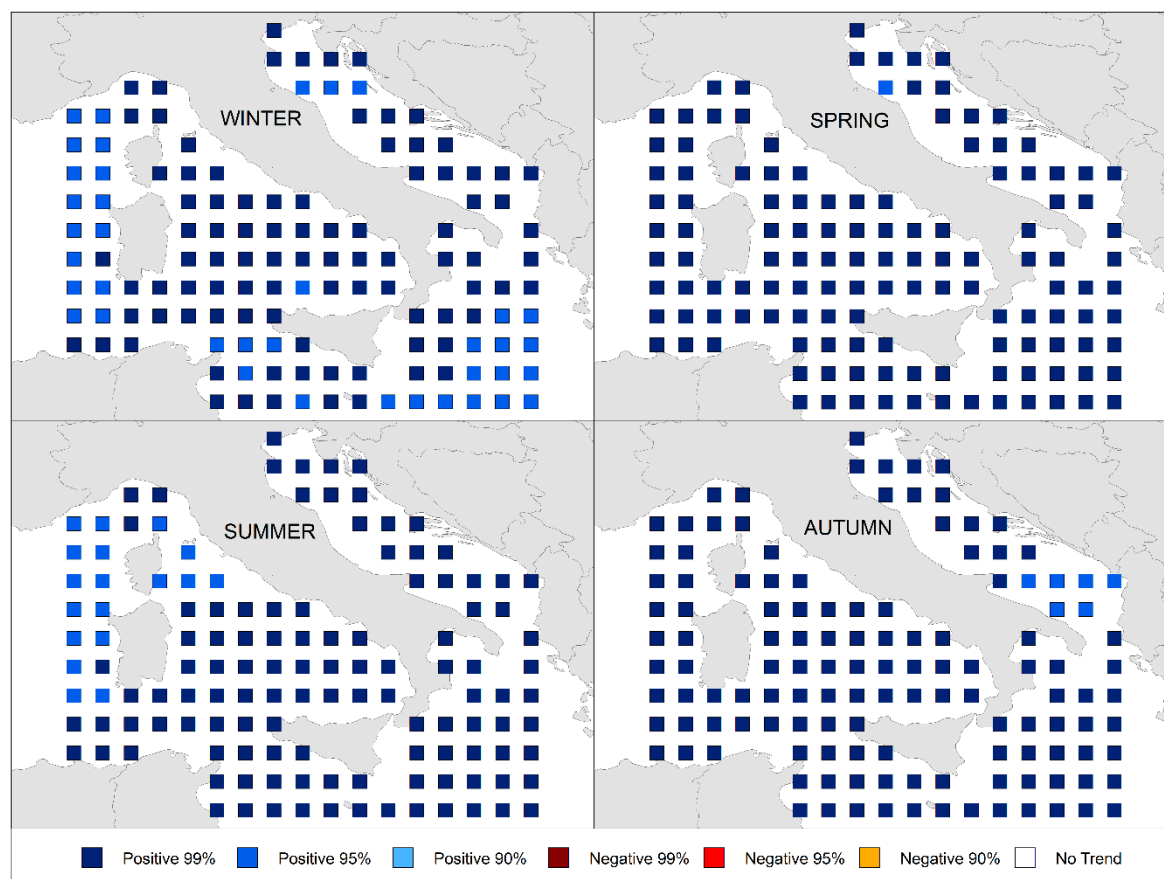


Figure 3. Spatial distribution of the seasonal trend of the mean values of T_e off the Italian coasts.

A seasonal trend analysis has been also performed on P and results are shown in Figure 4. In this case, as in the case of H_s , a strong variability for the trends during the four seasons occurs. Indeed, a combination of positive and null trends for P appears. In winter (Figure 4), the majority of the wave nodes show a null trend, with the exception of some nodes located especially in the Ionian Sea, where positive trends with a significance level of 90% have been observed. During spring (Figure 4), a significant rate of the wave nodes highlights a positive trend with significance levels of 90% and 95%. These nodes are mainly concentrated in the Tyrrhenian and Ionian Seas. A few nodes located in the southern part of the Tyrrhenian Sea show a positive trend with a significance level of 99%. No trends in this season have been detected in the Adriatic and the Ligurian Seas or in the western part of the Sardinia. During summer (Figure 4), a remarkable positive trend with a significance level equal to 99% has been detected in the Ionian Sea and in the northern area of the Adriatic Sea. The other areas of the Italian Seas highlight positive trends with a lower significance level. Null trends have been detected in the Ligurian Sea. For the last involved season, i.e., autumn (Figure 4), the spatial distribution of the trends is similar to summer. Indeed, positive trends with a significance level of 99% occur in the same seas, with the addition of the western part of the Tyrrhenian Sea. Positive trends with a lower significance level have been principally detected in the eastern part of the Tyrrhenian Sea, in the central part of the Adriatic Sea and close to Sardinia. The majority of null trends have been observed in the southern part of the Adriatic Sea.

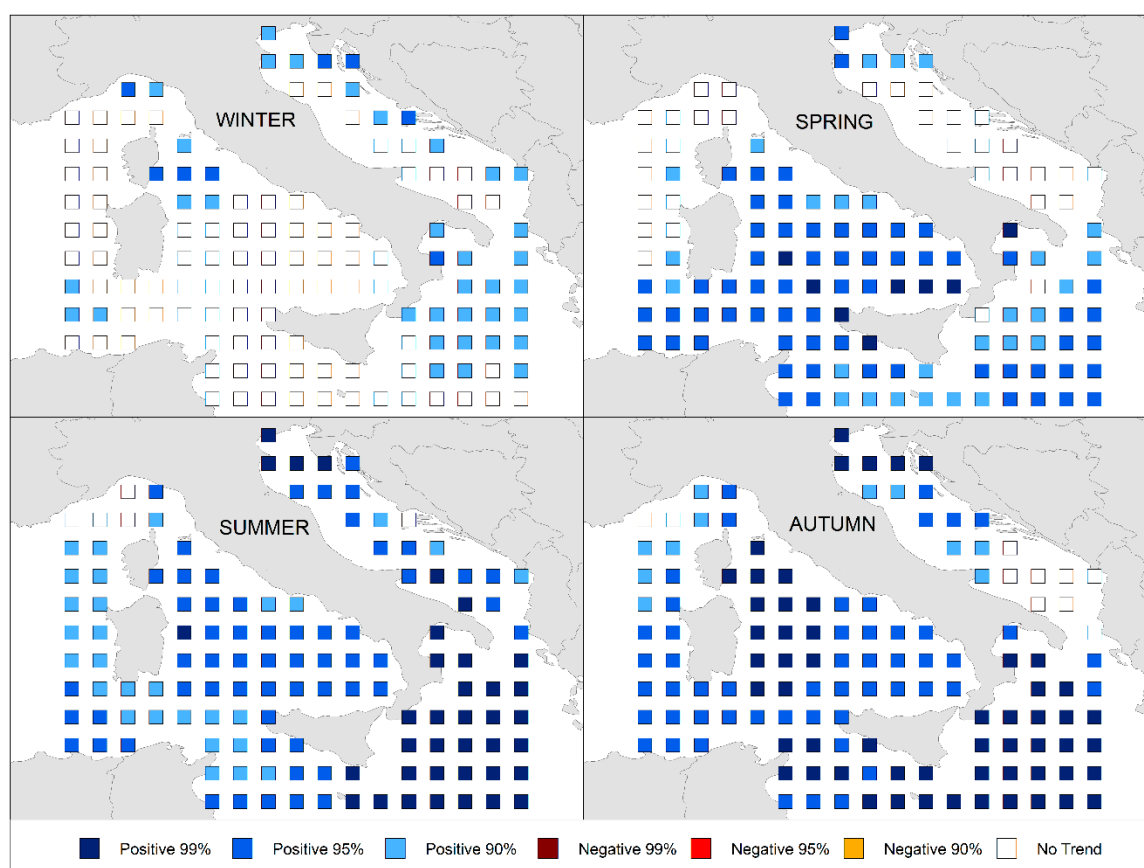


Figure 4. Spatial distribution of the seasonal trend of the mean values of P off the Italian coasts.

4. Conclusions

A statistical trend analysis of the mean annual and seasonal values of significant wave energy, energy period and wave power has been performed in the Italian Seas. For this purpose, a 40-year-long time series of waves deduced from the global atmospheric reanalysis ERA-INTERIM by the ECMWF has been considered. The Mann–Kendall non-parametric test has been used to identify possible trends.

Regarding the statistical results at an annual scale, the majority of the wave nodes involved highlight positive trends with a significance level of 99% for H_s . When T_e is considered, all wave nodes show positive trends with a significance level of 99%. Regarding P , this quantity shows the highest spatial variability in the Italian Seas. In any case, positive trends with different significance levels have been detected, with the exception of the Ligurian Sea and along the Adriatic Sea, where null trends appear.

Concerning the seasonal trend analysis applied to the Italian Seas, a higher percentage of variability has been observed if compared to the annual analysis, particularly for H_s and P . Specifically, in the Ionian Sea, positive trends with high significance levels have been detected for the three variables involved. It has also been observed that positive trends occur in most of the other seas and, especially, in the Tyrrhenian Sea. The autumn season highlights the highest percentage of positive trends with a significance level equal to 99%, while winter represents the season with the highest frequency of null trends.

The obtained results, if confirmed in the future, could have significant impacts on the morphodynamic evolution of the coasts, with a possible increase in erosion phenomena. Furthermore, the general increase in wave power could be useful to identify possible locations of marine sites for the installation of WECs for electricity purposes.

Further analyses will be dedicated to identifying possible annual and seasonal trends linked to extreme values of H_s , T_e and P , and how they influence the magnitude of the design waves.

Author Contributions: Conceptualization, T.C. and F.A.; methodology, T.C. and F.A.; formal analysis, T.C.; resources, D.A.F.; writing—original draft preparation, T.C. and F.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The ECMWF wave data were provided by the MARS archive under the authorization of the Italian Air Force.

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

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