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Exploring Recent (1991–2020) Trends of Essential Climate Variables in Greece

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Abstract: Europe and the Mediterranean are considered climate change hot spots. This is the reason why this paper focuses on the analysis of the trends of essential climate variables in a Mediterranean country, Greece. The analyzed period is 1991–2020, and the dataset used is ERA5-Land (produced by the European Center for Medium-Range Weather Forecasts), which has global coverage and an improved resolution of ~9 × 9 km compared to other datasets. Significant climatic changes across Greece have been put in evidence during the analyzed period. More specifically, the country averaged a 30-year trend of temperature of +1.5 °C, locally exceeding +2 °C, and this increasing trend is positively correlated with the distance of the areas from the coasts. Accordingly, the number of frost days has decreased throughout the country. In terms of rainfall, a major part of Greece has experienced increasing annual rainfall amounts, while 86% of the Greek area has experienced a positive trend of days with heavy rainfall (>20 mm). Finally, a multiple signal of the trend of consecutive dry days was found (statistically non-significant in the major part of Greece).

Keywords: climatology; Greece; trend analysis; air temperature; sea surface temperature; precipitation; drought

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1. Introduction

Evaluating the trends of essential climate variables such as temperature (air and sea) and precipitation over recent decades is crucial for establishing the scientific foundation of climate change in a specific region of our planet. A comprehensive analysis of current climatic trends allows for the assessment of the magnitude of changes, particularly in air temperature, sea surface temperature and precipitation patterns. The global and regional impacts of climate change include stress on agricultural and natural ecosystems [1,2], alterations in water availability [3], economic losses due to the increased frequency of high-impact weather events [4,5], and impacts on health [6,7]. Consequently, this paper focuses on analyzing the trends in essential climate variables [8] within the Greek territory.

According to many climate assessments (e.g., [9]), Europe and specifically the Mediterranean area have already experienced significant changes in essential climate variables (e.g., temperature and precipitation) with respect to mean values of the recent decades (1991–2020). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) [10] details the impacts of climate change on Europe, including the Balkans, highlighting increasing trends in temperature, changes in precipitation patterns and increased frequency of extreme weather events. According to these latest assessments, the Balkan area has experienced significant warming over the past century. This warming trend has accelerated in recent decades, and the average temperature increase in the region is higher than the global average. For the observed precipitation trends in the Balkans, the trends are more variable compared to temperature. Some areas have experienced decreases in annual precipitation, while others have seen increases. There has also been a notable change in the seasonal distribution of precipitation, with more intense rainfall events and longer dry periods [10].

More specifically, the study of Lionello and Scarascia [11] highlights the climate sensitivity of the Mediterranean Basin by showing that this region warms about 20% faster than the global average, with significant summer and daytime increases. Precipitation is mostly decreasing, negatively impacting crops and water resources. Similarly, Zittis et al. [12] found that the Eastern Mediterranean and Middle East regions are warming nearly twice as fast as the global average, with severe heatwaves and a projected increase of up to 5 °C by this century's end. Precipitation may decrease by 20–30%, exacerbating droughts as greenhouse gas emissions keep rising. Moreover, Urdiales-Flores et al. [13] investigated temperature trends in the Mediterranean basin over a very long period (last 120 years) and identified the area as the fastest-warming area in the globe. The authors attributed this fast warming to the increasing radiative forcing of greenhouse gases.

Recent studies on temperature and precipitation trends in Greece have primarily focused on local weather station data, particularly in densely populated areas such as Athens, or have used climate models. Founda et al. [14] analyzed historical daily precipitation data (1860–2008) from the National Observatory of Athens (NOA) and found no statistically significant long-term trends in annual and seasonal precipitation. However, the last three decades revealed negative anomalies in the number of rainy days per decade, with a notable increase in heavy (>30 mm/day) and extreme (>50 mm/day) precipitation events. Future projections, validated through an ensemble of regional climate models, predict a 35% decrease in mean annual precipitation for the period 2051–2100, along with an increase in heavy and extreme precipitation, raising concerns about water deficits and drought risk in the region. Additionally, a recent study on the Regional Precipitation Index (RPI) operationally used by NOA [15] identified a significant positive trend in category 3 or greater of RPI (i.e., heavy rainfall) during the period 1991–2020, based on daily ERA-Land reanalysis data [16]. Varlas et al. [17] used ERA5 monthly data to study annual and seasonal trends of precipitation for a 71-year period from 1950 to 2020 and to quantify nonlinear variabilities in the monthly precipitation time series. Their results showed primarily declining inter-annual precipitation trends, which were mostly significant in winter and over western Greece and the eastern Aegean Sea. Most interestingly, their analysis revealed that monthly precipitation over Greece was characterized by high inter-decadal variability, increasing from 1950 to 1960, consequently decreasing until the early 1990s, and then increasing at a smaller rate until 2020.

As it concerns temperature trends in Greece, Founda et al. [18] analyzed the historical climatic records of NOA since 1864, showing that Athens' air temperature has fluctuated significantly since the mid-19th century, reflecting Northern Hemisphere trends. Since the mid-1970s, a notable warming trend has been observed, especially in summer, with more frequent, intense and earlier summer heatwaves. This underscores the complex interplay between urbanization, natural climate variability and global warming in Athens' climate. Papakostas et al. [19] used an hourly temperature time series from 1983 to 2012 from Athens and Thessaloniki meteorological stations and found a significant increasing trend in ambient temperatures over three decades. The average temperature increase was 1.2 °C in Athens and 1.1 °C in Thessaloniki. The frequency of high-temperature occurrences increased while low-temperature occurrences decreased, indicating milder winters and hotter summers. The authors have also highlighted that this climate change trend affects building energy demands, particularly increasing cooling needs, impacting energy production and design considerations for buildings. Mamara et al. [20] conducted an extensive analysis of temperature trends in Greece, utilizing weather station data spanning from 1960 to 2004. Their findings revealed a pronounced warming trend, particularly evident in the last decade of the study period. Significant shifts in temperature regimes were identified starting from the mid-1980s. The study highlighted a cooling period in winter temperatures between 1991 and 1994, followed by a warming phase commencing in the mid-1990s. Both annual and seasonal analyses indicated a marked warming trend from 1976 to 2004, with the most significant increases observed in northern Greece, particularly during the summer and autumn seasons.

The paper is structured as follows: Section 2 presents the datasets used for the analyses, while the results are presented in Section 3. Section 4 is devoted to the discussion of the results and the final remarks of this work.

2. Materials and Methods

The analysis performed in this study focuses on some of the main essential climate variables that are widely used for understanding climate variability, including air temperature, precipitation and sea surface temperature. Many studies, so far, have investigated basic meteorological parameter trends using either station data or coarser resolution reanalysis data (e.g., ERA5, at $0.25° \times 0.25°$ spatial resolution). Although both approaches are valid and provide meaningful and robust results, they suffer (a) from a restricted geographical representation (when using surface station data) and (b) from a coarse resolution when using well-known datasets such as ERA5. For these reasons, the analysis performed in the frame of the present study is based on the recently available dataset of ERA5-Land.

The primary data are provided by the Copernicus Service of the European Commission [21]. ERA5-Land, produced by the European Center for Medium-Range Weather Forecasts (ECMWF), has global coverage and temporal data availability that began in 1981 [16]. The data have an improved resolution of ~9×9 km compared to other datasets (e.g., ERA5), while the temporal frequency is hourly. The analysis is based on temperature and precipitation data, available for download at https://cds.climate.copernicus.eu/ (accessed on 15 August 2024).

It is worth noting that according to Sheridan et al. [22], who performed a comparative study of three reanalysis products (ERA5, ERA5-Land and NARR), the higher spatial resolution provided by ERA5-Land permitted to accurately reproduce extreme events, especially in topographically complex areas. Moreover, Zhao and He [23] recently mentioned that ERA5-Land reanalysis captures the observed global increasing trend in temperature very well, even in mountainous areas in China. Finally, Gomis-Cebolla et al. [24], comparing ERA5-Land data against in situ observations in Spain, concluded that this dataset has a good capacity to reproduce the spatial patterns and temporal trends of the observations.

As it concerns sea surface temperature, the Copernicus High-Resolution Level 4 Sea Surface Temperature Reprocessed dataset [25] was used. This dataset, available on a 0.05° resolution grid over the Mediterranean, comprises daily (nighttime) sea surface temperature estimates derived from satellite observations.

The analysis of the evolution of climate variables in Greece focuses on the period 1991–2020, and the calculated trends were tested for their statistical significance. More specifically, linear regression with the Theil–Sen non-parametric method was employed to determine the trend's slope, and the Mann–Kendall non-parametric test was used to assess the statistical significance at the 95% confidence level.

Figure 1 shows the main topographic features, as well as key geographic districts of Greece, mentioned later in the text. Greece, located in southeastern Europe, exhibits a climatological diversity that is significantly shaped by its geographical position, varied topography, and proximity to the Mediterranean Sea. The climate across Greece can be categorized into three primary types: Mediterranean, Alpine and temperate.

The Mediterranean climate predominates in the coastal regions, including the islands and much of the southern mainland. This climate is characterized by hot, dry summers, with temperatures frequently surpassing 30 °C, and mild, wet winters, where temperatures typically range from 10 °C to 15 °C. The period from November to February marks the peak of the wet season.

Northern Greece is primarily influenced by a temperate climate, where summers are warm, albeit cooler compared to the Mediterranean regions, and winters are notably colder, with temperatures fluctuating between −5 °C and 10 °C. Precipitation in this region is evenly distributed throughout the year, with a slight increase during the winter months, which also brings frequent snowfall and frost.

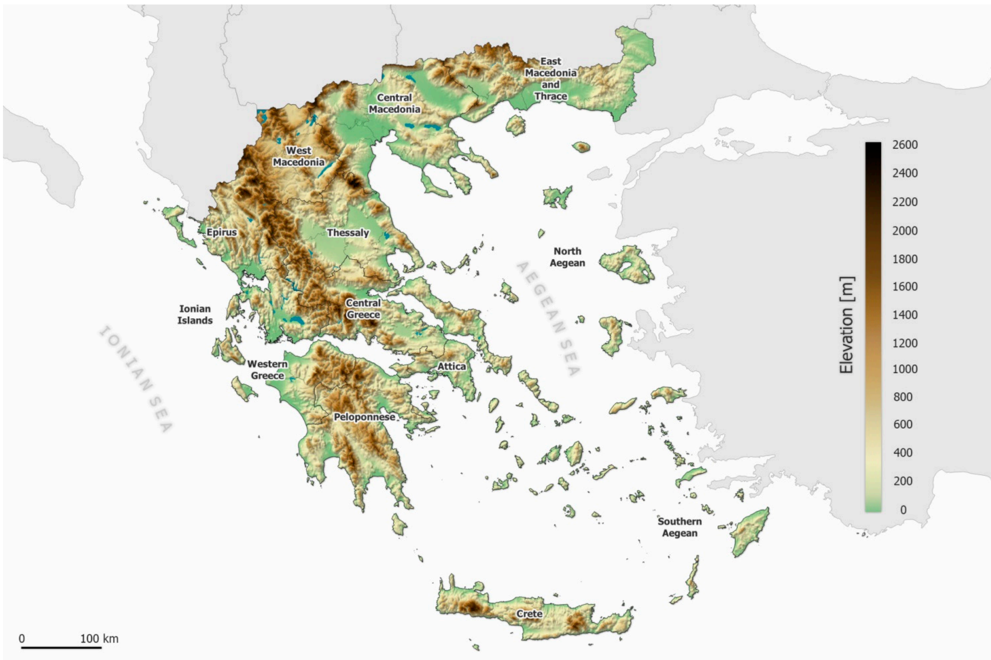

Figure 1. Topographic map of Greece (elevation in m) and locations referred to in the text.

In the mountainous regions, particularly at higher elevations, the Alpine climate prevails. This climate is characterized by cool, frequently rainy summers and cold winters that are often accompanied by heavy snowfall.

3. Results and Discussion

3.1. Temperature and Frost Days Trend

Figure 2 shows the trend of the average yearly temperature during the period 1991–2020 throughout Greece (continental and insular), which is increasing, while this increase is statistically significant. On average, the increasing trend is ~0.05 °C per year, which means that cumulatively, the average temperature in the country has increased by about 1.5 °C in the last 30 years. It is noted here that this increase has also been confirmed by the measurements of meteorological stations in various regions of the country, e.g., in the center of Athens, the most populated city of Greece [20].

This increasing trend shows, however, an interesting geographical variability. More specifically, in many regions, mainly in Northern Greece (far from the seashore), the increasing trend exceeds 0.07 °C per year, which means that the cumulative trend of the average temperature in the last 30 years in these regions was greater than ~+2 °C. It should be noted that similar positive trends are also evident for the daily maximum and minimum temperature The estimation of the percentage of the Greek territory that experienced large cumulative trends of air temperature in the last 30 years reveals that 48% of the Greek area has experienced a cumulative increasing trend larger than +1.5 °C and 7% over larger than +2 °C.

In order to investigate the role of the "continentality" (expressed as the distance of each ERA5-Land grid point from the coast) on the yearly temperature trend, a scatter plot between the yearly trends of mean temperature against the distance from the coast is shown in Figure 3. As already inferred from Figure 2, the land points that are close to the coast show a yearly trend of the order of 0.045 °C per year, and this trend is increasing gradually as we move far from the coasts, exceeding 0.06 °C up to almost 0.08 °C per year for the areas that are farther than 100 km from the coasts.

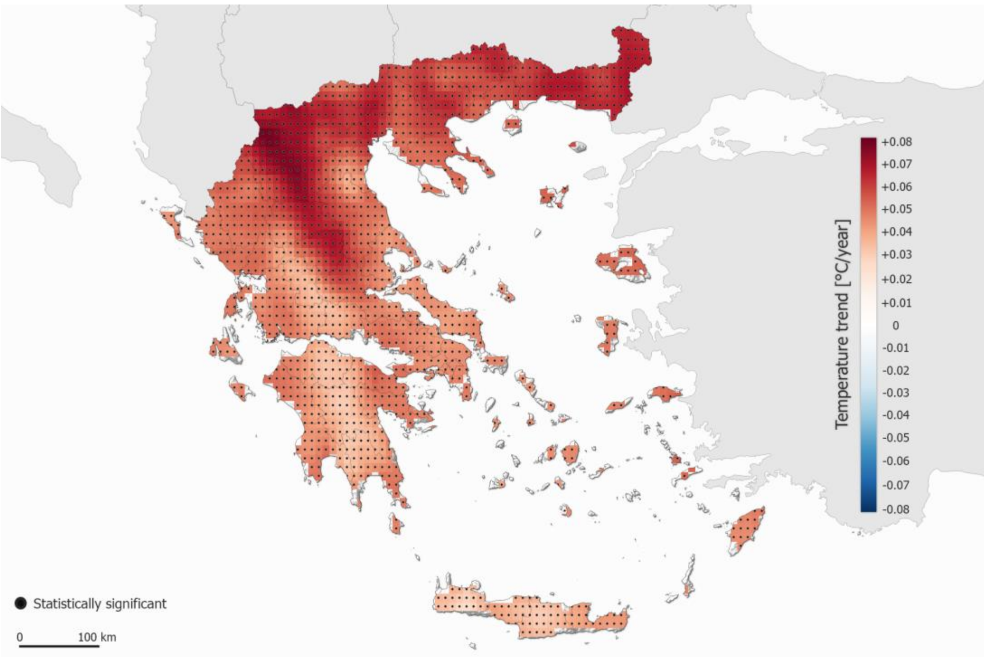

Figure 2. Mean yearly temperature trend during the period 1991–2020. Dotted areas indicate trends that are statistically significant.

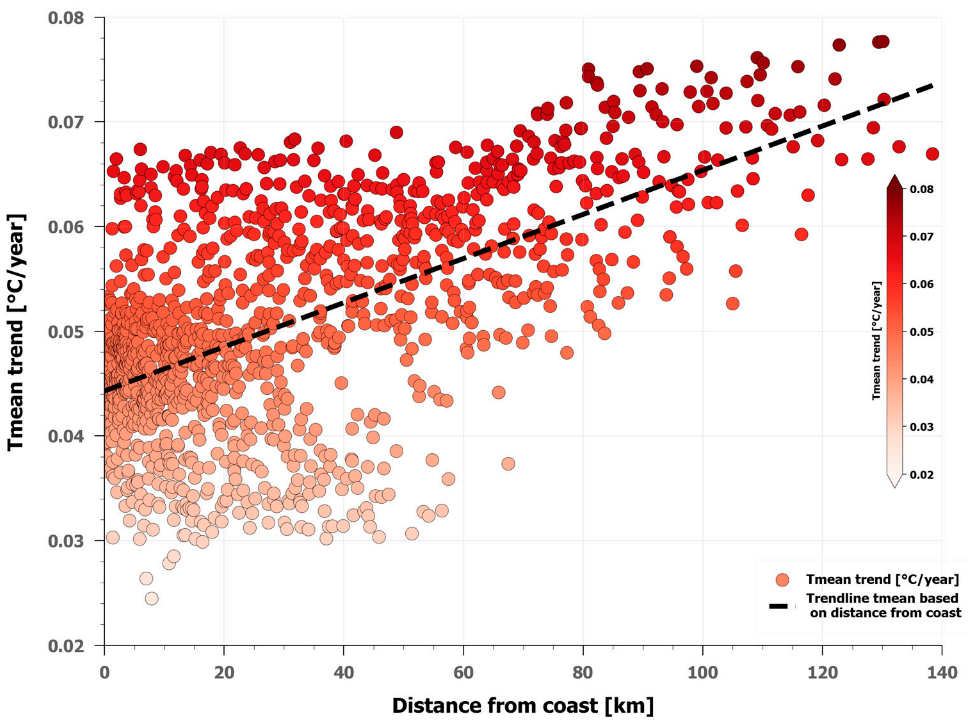

Figure 3. Scatterplot of mean yearly temperature trend during the period 1991–2020 against distance from the coast.

It is of interest to further discuss the temperature trend per decade, as shown in Figure 4. If the 30-year period is split into three decades, some interesting outcomes arise, as follows:

(a) In all three decades, the trend is increasing, with no significant differences in the increasing trend;
(b) After the year 2012, all subsequent years show a mean temperature over Greece that is greater than the 30-year average (14.1 °C);
(c) The geographical distribution of temperature deviation from the 30-year average value shows, as expected, a relatively cold first decade (1991–2000), with deviations up to −0.8 °C (mainly over continental Greece), while the last decade (2011–2020) is warmer than the 30-year average value, reaching up to +1 °C in the northwestern part of Greece.

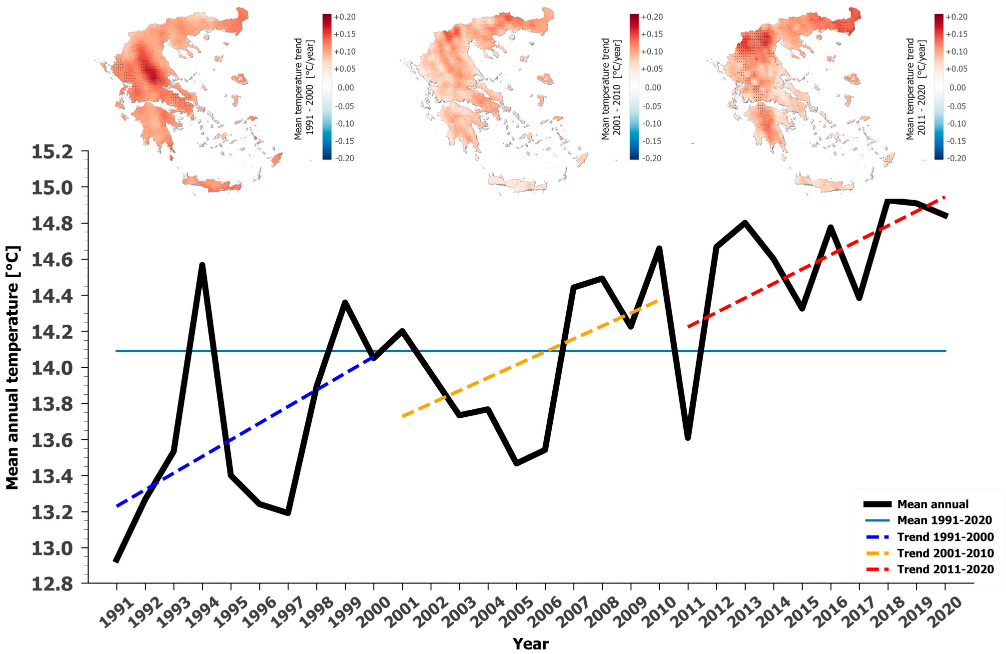

Figure 4. Yearly evolution of mean temperature during the period 1991–2020. The blue line denotes the 30-year average value. The dotted lines show the trend for each of the three decades. On top of the graph, the geographical distribution of the temperature deviations of each decade from the 30-year average is shown.

The trend of temperature patterns related to extremes, such as heatwaves, has been recently studied based on ERA5-Land data. Galanaki et al. [26] analyzed heatwave occurrences over Greece for the period 1950–2020 and identified that heatwaves have become more frequent, longer and more intense during the study period. Recently, Pantavou et al. [27] provided estimates and trends of thermal bioclimate in Greece based on the Universal Thermal Climate Index (UTCI) during the period 1991–2020. The authors identified an increasing trend in mean annual UTCI (mean = 0.05 °C/year), more pronounced in higher latitude regions.

Therefore, in the frame of the present study, we focus on another important factor of temperature extremes, namely the frost days trend, a parameter of great importance and impact on agriculture. Figure 5 shows the trend of frost days (minimum day temperature below 0 °C) during the period 1991–2020. As can be seen in the Figure, throughout Greece, this trend is negative and, in most areas, statistically significant. On average, the decreasing trend is ~0.3 days per year, which means that the cumulative decreasing trend of the number of frost days in the last 30 years is ~10 days. Following the pattern seen in the mean temperature trend (Figure 2), the largest decrease in frost days is evident in the northwestern mainland of Greece, with a decreasing trend approaching −1.2 days per year or cumulatively ~35 days in the last 30 years.

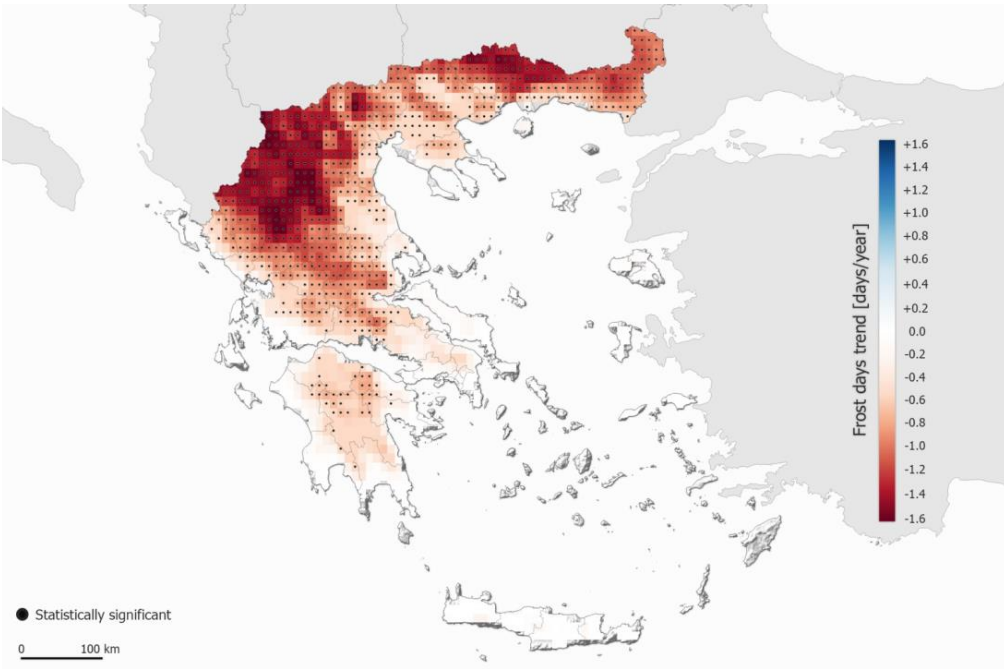

Figure 5. Number of frost days trend during the period 1991–2020. Dotted areas indicate trends that are statistically significant.

3.2. Sea Surface Temperature

Sea surface temperature is also an essential climate variable that needs to be continuously monitored and assessed. Figure 6 shows the trend of the average sea surface temperature during the period 1991–2020. All Greek seas significantly warmed during the elapsed 30 years, with a maximum increasing trend of 0.08 °C per year in the Northern Aegean Sea, Ionian Sea and the waters surrounding Crete Island. These values correspond to a cumulative increase of 1.5 °C within the analyzed period. This result is of paramount importance, not only for marine biodiversity (a subject beyond the scope of this study) but for air–sea interaction mechanisms and enhanced evaporation from the warmer sea surface. For instance, warmer-than-average Mediterranean waters were a contributing factor to the deepening of Medicane Ianos that affected Greece in September 2020 with extended disasters, including human fatalities [28].

The sea surface temperature trend per decade is shown in Figure 7, revealing the following:

(a) In all three decades, the trend is increasing, with a larger increasing trend during the decade 1991–2000;
(b) After the year 2009, all subsequent years show a mean sea surface temperature over the Greek seas that is greater than the 30-year average (19.7 °C);
(c) The geographical distribution of the sea surface temperature deviation from the 30-year average value shows, as expected, a relatively cold first decade (1991–2000), with deviations up to −0.6 °C (mainly over the northern Aegean Sea), while the last decade (2011–2020) is warmer than the 30-year average value, reaching up to +0.8 °C, especially over the Ionian Sea coasts and the maritime area south of Rhodes island.

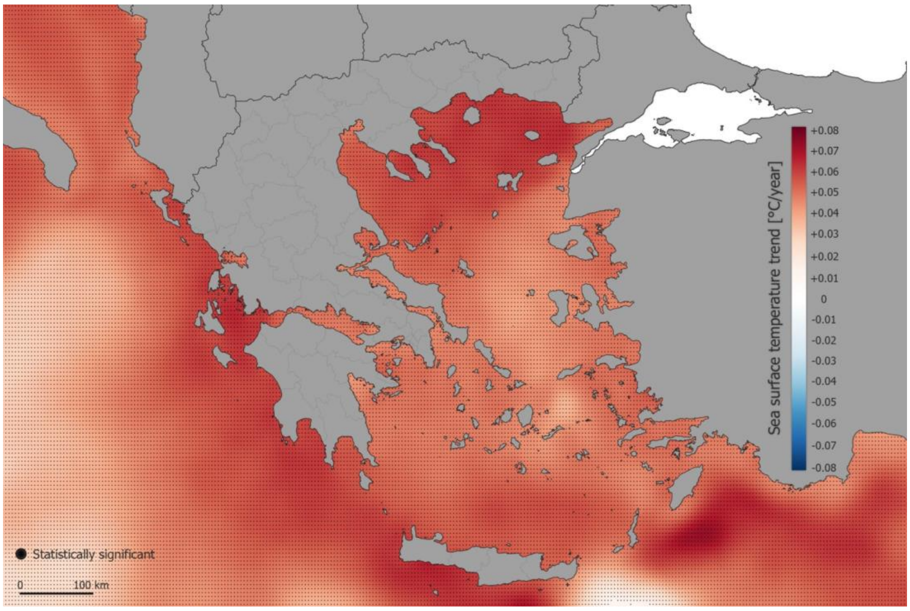

Figure 6. Mean yearly sea surface temperature trend during the period 1991–2020. Dotted areas indicate trends that are statistically significant.

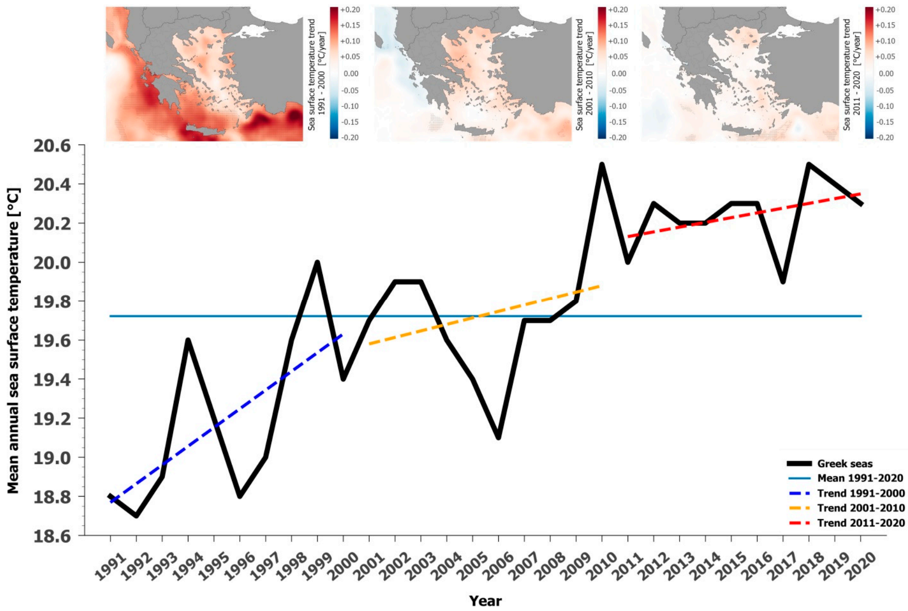

Figure 7. Yearly evolution of sea surface temperature during the period 1991–2020. The blue line denotes the 30-year average value. The dotted lines show the trend for each of the three decades. On top of the graph, the geographical distribution of the sea surface temperature deviations of each decade from the 30-year average is shown.

3.3. Precipitation

Figure 8 shows the precipitation trend during the period 1991–2020. As can be seen in the Figure, there is an increase in rainfall in areas of Epirus and the Ionian Islands, which locally reaches 12–15 mm per year, and this increasing trend is statistically significant. This increase is mainly due to a large increase in precipitation that occurred during the last decade (2011–2020) of the analyzed period.However, there are limited areas characterized by a decreasing trend of rainfall, mainly in Central Thessaly, Eastern Peloponnese and Eastern Crete. This finding is in line with Varlas et al.'s [17] results, based on coarser data (ERA5) for the period 1950–2020, indicating a small increase in rainfall trend.

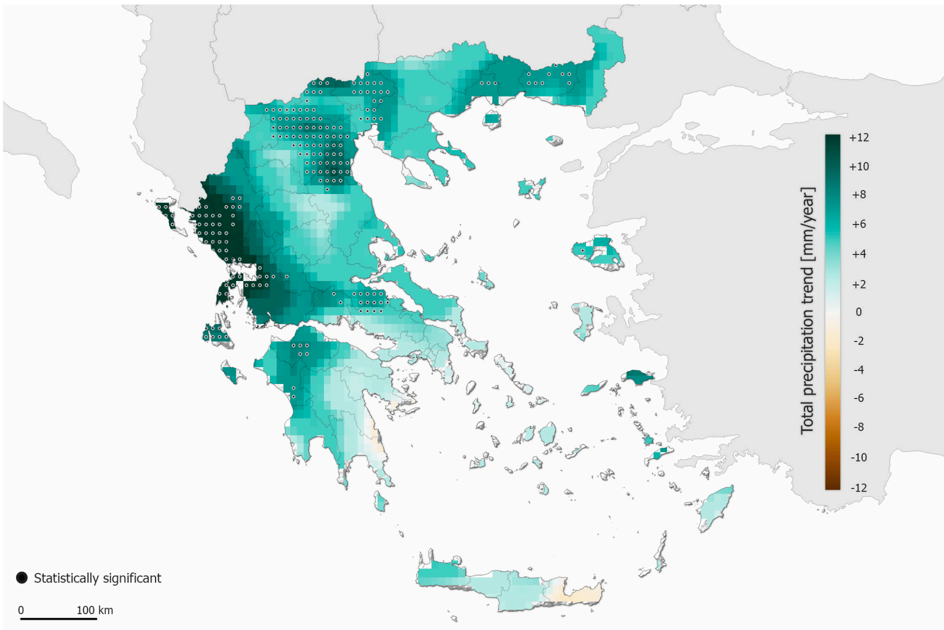

Figure 8. Precipitation trend during the period 1991–2020. Dotted areas indicate trends that are statistically significant.

If we focus on the number of days with heavy rainfall (number of days with daily rainfall greater than 20 mm), it is evident that within the analyzed period (1991–2020), the number of days with heavy daily rainfall shows an increasing trend in many areas (e.g., Western Greece, East Macedonia and Thrace) which locally reaches 0.3 days per year, or cumulatively ~9–10 days in the 30-year period (Figure 9). Therefore, the number of days with heavy rain is increasing, and this increase is a very important factor in studying the effect of heavy rainfall on many economic sectors, as well as the impact on civil protection since the increasing trend is related to more frequent flood-producing events, as also identified by Lagouvardos et al. [15].

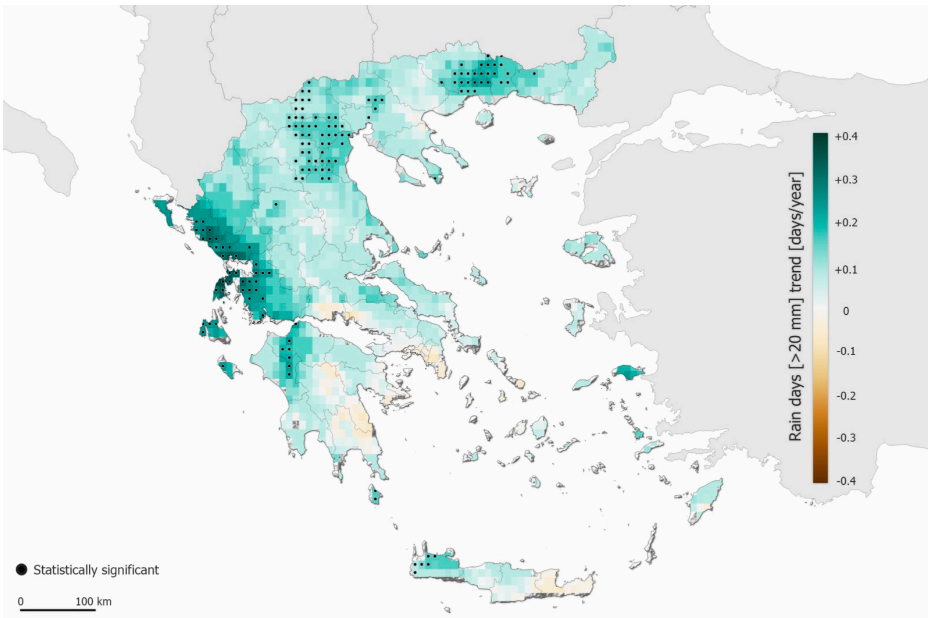

Figure 9. Trend of heavy precipitation days during the period 1991–2020. Dotted areas indicate trends that are statistically significant.

On the contrary, there are areas with a negative trend in the number of days with heavy rainfall, such as in Central Thessaly, Eastern Peloponnese and areas of Crete. As an average, 86% of the Greek area has experienced a positive trend in days with heavy rainfall and only 7% with a negative trend.

3.4. Drought

Droughts are known to have a significant impact on the environment, agriculture and economy, and they affect, in various ways, more people than any other type of natural disaster worldwide. A drought can be classified as a meteorological, agricultural, hydrological or socio-economic hazard based on the considered and expected impacts. For the purposes of this study, we consider drought from a meteorological perspective based on the calculation of the well-known climate index of consecutive dry days (CDD), which is defined as the maximum number of consecutive days with less than 1 mm of precipitation.

Figure 10 shows the CDD trend over Greece during the period 1991–2020. A large part of the northern part of the country, which also includes areas with large agricultural production, presents an increasing trend in the CDD. On the contrary, parts of southern continental Greece, as well as the Aegean islands and Crete, present a significant decrease in the CDD. As stated before, the last decade (2011–2020) of the analyzed period is a period with increasing precipitation, and therefore, this decade strongly influenced the decreasing trend of CDD in the southern part of the country.

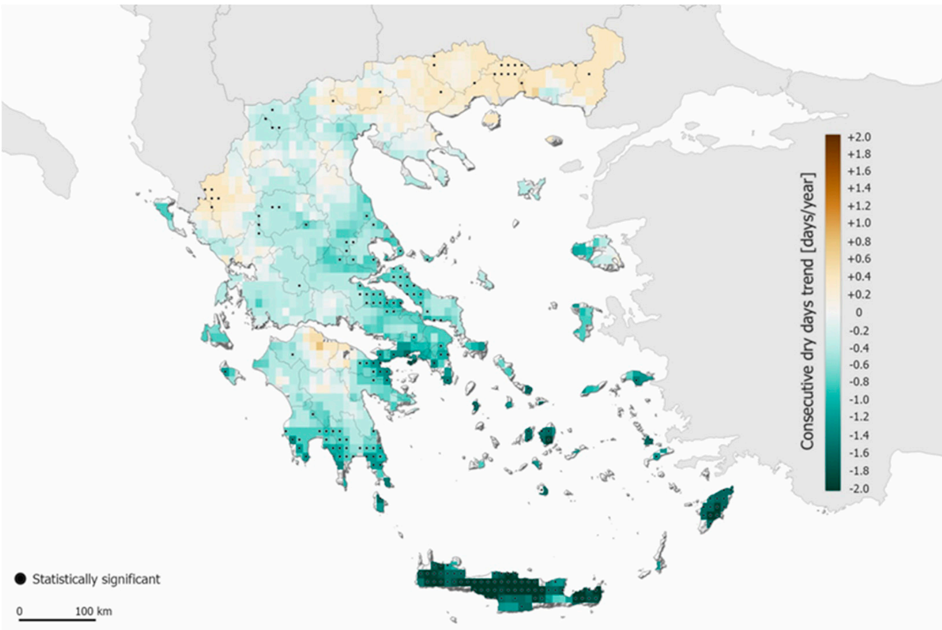

Figure 10. Consecutive dry days (CDD) trend during the period 1991–2020. Dotted areas indicate trends that are statistically significant.

4. Concluding Remarks

Using the high-resolution ERA5-Land dataset as well as high-resolution sea surface temperature data, a trend analysis of selected essential climate variables has been performed for the period 1991–2020, demonstrating the following:

- The increasing cumulative 30-year trend of temperature reaches a country-averaged value of +1.5 °C, while locally, it exceeds +2 °C mainly in the northwestern part of Greece. This trend is much higher than the global temperature trend of ~0.6–0.8 °C during the same period [29]
- The distance from the coasts was found to be positively correlated to the increasing temperature trend. Areas remote from the sea experienced a higher increasing trend during the analyzed period, compared to the coastal areas and the islands. This finding

is of great importance for sectors such as agriculture in the areas where the increasing temperature trend maximizes;
- Following the monotonic increase in air temperature, frost days, a key parameter for agriculture, shows a significant decrease during the analyzed period;
- Sea surface temperature reaches an average cumulative increasing 30-year trend of 1.5 °C. A faster increase in sea surface temperature was evident during the first decade (1991–2000) of the analyzed period. Higher SSTs are related to more enhanced evaporation and hence increased atmospheric moisture, thus increasing extreme precipitation, especially in the coastal regions [30];
- Annual precipitation shows a mixed signal. In western Greece, there is a significant increase in precipitation, while in the eastern part of continental Greece, the Aegean Islands and Crete, a decrease in annual precipitation is evident (although not statistically significant);
- Days of heavy rainfall show a significant increase, mainly in the western part of the country. This finding reveals the potential danger of flood events in these areas;
- Consecutive dry days also show a mixed signal. Large areas of northern Greece show an increasing trend of the CDD, while large parts of eastern and southern Greece (including the Aegean Islands and Crete) show a decreasing trend of CDD, a fact that is beneficial to agriculture. This decrease seems to be related to the increase in rainfall that was observed during the last decade (2011–2020).

The above reveals significant climatic changes across Greece between 1991 and 2020. In more detail, the near-surface air temperature trend presents a clear, statistically significant positive sign, with regional differences, indicating that the actual climatic "hot-spot" (in terms of the largest cumulative trend over the 30-year period) in Greece is the area of northwestern Greece, i.e., the area with the higher degree of continentality. This trend was already evident in climate simulations for the eastern Mediterranean about 20 years ago [31,32], with warnings from scientists regarding the consequences of the increasing number and amplitude of extreme temperatures in the economy of Greece [33].

Moreover, sea surface temperature also shows a clear positive trend in this study, with cumulative values of ~1.5 °C throughout the Greek seas, similar to previous studies using different datasets (e.g., [34]). Although we only investigate the sea surface temperature, it has been shown that increasing water temperature in the Mediterranean affects the aqua flora and fauna [35–37].

Precipitation trend is less clear. Although the first decade of the analyzed period was dry (especially the first years of 1990), excessive rainfall during the last decade (2011–2020) led to a small positive trend throughout the country, while the positive trend is more pronounced in the western part of Greece. Previous studies using in situ and reanalysis data have also shown mostly non-significant trends in the Mediterranean region (e.g., [38,39]). The same pattern is also evident when analyzing the number of consecutive dry days. It should be noted, however, that rainfall is only a part of the hydrological cycle, and therefore, snow accumulation is also another important factor to investigate, a work under realization by our scientific team.

Author Contributions: Conceptualization, K.L. and V.K.; methodology, S.D. and V.K.; software, G.K. and C.G.; investigation, ALL; data curation, S.D. and G.K.; writing—original draft preparation, ALL; writing—review and editing, ALL; visualization, G.K.; supervision, K.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: ERA5-Land data used in this study for the period from 1991 to 2020 are available at: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=

overview (accessed on 26 June 2024). Sea surface data from Copernicus are available at: https://data.marine.copernicus.eu/product/SST_MED_SST_L4_REP_OBSERVATIONS_010_021/description (accessed on 26 June 2024).

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

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