

Article

Four Decades of Surface Temperature, Precipitation, and Wind Speed Trends over Lakes of Greece

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Abstract: Climate change is known to affect world's lakes in many ways. Lake warming is perhaps the most prominent impact of climate change but there is evidence that changes of precipitation and wind speed over the surface of the lakes may also have a significant effect on key limnological processes. With this study we explored the interannual trends of surface temperature, precipitation, and wind speed over 18 lakes of Greece using ERA5-Land data spanning over a period of almost four decades. We used generalized additive models (GAMs) to conduct time-series analysis in order to identify significant trends of change. Our results showed that surface temperature has significantly increased in all lakes with an average rate of change for annual temperature of $0.43\text{ }^{\circ}\text{C decade}^{-1}$. With regard to precipitation, we identified significant trends for most lakes and particularly we found that precipitation decreased during the first two decades (1981–2000), but since 2000 it increased notably. Finally, wind speed did not show any significant change over the examined period with the exception for one lake. In summary, our work highlights the major climatic changes that have occurred in several freshwater bodies of Greece. Thus, it improves our understanding on how climate change may have impacted the ecology of these important ecosystems and may aid us to identify systems that are more vulnerable to future changes.

Keywords: Greek lakes; surface temperature; climate change; time-series; ERA5-Land climate reanalysis



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1. Introduction

The epoch of Anthropocene includes all human-induced global changes of the natural environment, such as climate change [1]. Lakes in particular are susceptible to various climate change impacts including lake warming and water level fluctuations [2,3]. Not surprisingly, scientists have provided multiple evidence of significant changes of climate-driven limnological variables that have occurred during the past few decades [4–8] from lakes worldwide. Apart from a significant rise of water temperature, changes in precipitation patterns and wind speed are expected to influence lake processes such as stratification, lake mixing, and eutrophication [8–11]. It becomes apparent that because these environmental changes pose multiple threats for both the water availability and the ecological integrity of these ecosystems, the adaptation of current freshwater management schemes to future climate-driven changes is a matter of top priority.

The Mediterranean region is particularly vulnerable to climate change as future projections show an increase in aridity that will likely induce a further reduction in water availability [12–14]. The impact of climate change is mostly associated with changes of seasonal variability as disparity between wet and dry season is expected to increase [15–17]. Studies have shown that in semi-arid regions, warming and reduced precipitation will result to lower water levels and higher nutrient concentrations, especially in shallow lakes [18,19]. Besides temperature and precipitation, there is growing evidence for atmospheric stilling (decrease of wind speed near surface) that influences limnological processes, mainly lake mixing and stratification [8,11]. Furthermore, future land use changes are

expected to enhance the impact of climate change on inland waters, mostly because of an increase in the demand for domestic and agricultural use of water [13]. Thus, changes in the climatic conditions are very likely to affect lake productivity and water quality with possible implications for biotic communities [9,20].

Greece has a diverse landscape which affects the spatial climatic variability [17,21]. Mediterranean climate is the dominant climatic type which shows a strong seasonal variability of rainfall. Furthermore, the unique topography of Greece is responsible for a clear discrimination of the climate with colder and wetter winters at northern-western mountainous areas in relation to southeastern lowlands [17,22]. This spatial variability influences the hydrology of the Greek lakes and other significant lake processes such as the thermal stratification and the mixing regime.

With this study we explored the interannual trends of surface temperature, precipitation, and wind speed over 18 lakes of Greece using ERA5-Land monthly averaged data from 1981 to 2020. We focused on these three parameters because several studies have revealed significant inter-annual changes that have occurred globally with severe impacts for the ecosystem functioning and structure of lakes. Based on the results from other studies we expected to find a significant rising trend of temperature, and a declining trend of precipitation and wind speed. Thus, our main objective was two-fold as we primarily aimed to identify significant trends of the three climate variables over the studied lake areas and then we attempted to quantify the change that have occurred within the last four decades. Overall, our study offers the opportunity to identify which lakes may have impacted the most by climate change and thus which are more sensitive to future changes. We expect that this information can be useful for other lake scientists that investigate the impact of climate change on certain biota of the studied lakes, or for managers and decision-makers that will have to consider the susceptibility of the lakes to climate change when they design and implement management plans.

2. Materials and Methods

2.1. Greek Lakes

The current analysis focused on 18 lakes of Greece (Figure 1). All lakes are included in the Pan-European network of Protected Areas “Natura 2000” as Sites of Community Importance (SCI), Special Areas of Conservation (SAC), and Special Protected Areas (SPA). The Prespa lakes and the artificial lake Kerkini are also characterized as “Wetlands of International Importance under the Ramsar Convention”. The importance of the lakes for the biodiversity conservation has been long recognized as the lakes are significant breeding and wintering areas for birds and host rich and diverse fish communities with high levels of endemism [23,24]. The lakes cover all biogeographic regions of mainland Greece [24] ranging from 37° to 41° N and 21° to 22° E. The altitude ranges from 16 to 853 m a.s.l (Table 1). Thus, the lakes reflect the high Greek landscape diversity and the increased variability in the climatic conditions. For a detailed description of the studied areas, see also Stefanidis et al., Stefanidis and Papastergiadou and Oikonomou and Stefanidis [23,25–27].

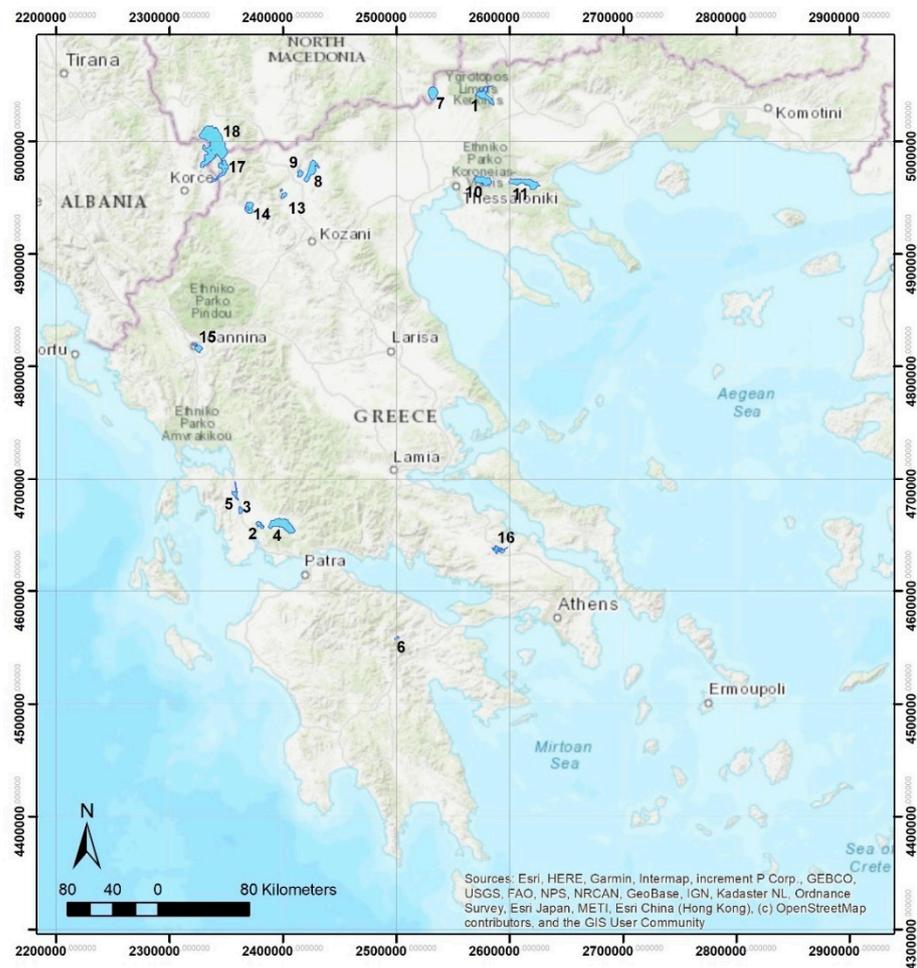


Figure 1. Map of Greece with the location of the 18 lakes. (1) Kerkini, (2) Lysimachia, (3) Ozeros, (4) Trichonida, (5) Amvrakia, (6) Stymfalia, (7) Doirani, (8) Vegoritida, (9) Petron, (10) Koronia, (11) Volvi, (12) Zazari, (13) Chimaditida, (14) Kastoria, (15) Pamvotida, (16) Iliki, (17) Mikri Prespa, (18) Megali Prespa.

Table 1. General characteristics of the lakes included in this study.

Lake	Latitude	Longitude	Altitude (m a.s.l)	Surface Area (km ²)	Max Depth (m)
Amvrakia	38°45'	21°11'	28	14.5	53
Chimaditida	40°36'	21°33'	593	10.1	3.5
Doirani	41°12'	22°45'	148	43.1	10
Iliki	38°24'	23°16'	78	19.1	-
Kastoria	40°30'	21°18'	629	30.0	9.1
Kerkini	41°11'	23°09'	30	70	10
Koronia	40°65'	23°65'	100	42.5	2
Lysimachia	38°34'	21°28'	16	13.5	9
Megali Prespa	40°46'	21°01'	852	266.0	55
Mikri Prespa	40°45'	21°05'	853	53.0	8.4
Ozeros	38°39'	21°13'	22	9.4	6.1
Pamvotida	39°40'	20°53'	470	22.0	11
Petron	40°45'	21°45'	527	14.4	5
Stymfalia	37°51'	22°27'	600	3.5	<2.5
Trichonida	38°34'	21°28'	18	96.5	58
Vegoritida	40°45'	21°45'	524	53.0	70
Volvi	40°41'	23°20'	37	68.6	23.5
Zazari	40°37'	21°33'	602	2.0	5.5

2.2. Climate Data

The climate data used in this study were retrieved from the ERA5-Land reanalysis dataset [28]. ERA5-Land has been produced by applying the latest version of the land surface model of the ERA5 climate reanalysis driven by the atmospheric forcing of ERA5 data [29]. ERA5 and, hence, ERA5-Land data are of the most qualitative reanalysis datasets worldwide, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and freely available by the Copernicus Climate Change Service (C3S). An advantage of ERA5-Land data is the high native horizontal resolution (9 km) while it also offers the capability of long-term hourly or monthly analyses as it covers a time period from 1981 to nearly present (2–3 months before). ERA5-Land provides high-quality information which can be exploited by various climatic studies and interdisciplinary analyses (e.g., [30–32]). For this study, we retrieved monthly averaged precipitation, skin temperature (considered as surface temperature), and wind speed data for a 39-year period from January 1981 to November 2020. Surface skin temperature has been widely used in research for exploring lake temperature dynamics mainly because it can be retrieved by satellite measurements. Although it can be highly variable, the temperature difference between the skin temperature and the surface water temperature is quite small [33]. In addition, skin temperature correlates strongly with the surface water temperature that is measured in situ which makes it ideal metric for assessing lake temperature trends. The data were provided in a regular latitude-longitude grid with a spacing of 0.1° , covering an area including the 18 lakes studied. The extraction of time series for each lake was performed considering the nearest ERA5-Land grid cell to each lake location, adopting the same methodology applied by Stefanidis et al. [22].

It is important to note here that surface skin temperature was chosen instead of air temperature at 2 m that is also included in the ERA5-Land dataset and usually used in climatic studies. This choice was based on the fact that skin temperature can capture instantaneous surface heat flux changes and, thus, it better represents the temperature at the upper ground surface. It is noteworthy that it is considered as the key parameter that is required to satisfy the surface energy balance. Because skin temperature is computed differently over land and water bodies, in the largest lakes studied here, i.e., Megali Prespa, Mikri Prespa, Volvi, and Trichonida, skin temperature represents water-surface temperature offering valuable and realistic information in our analysis. On the other hand, regarding the smaller lakes, it represents land-surface temperature. Therefore, it is expected to be characterized by larger variabilities consistent with changes in surface fluxes, however, it is still considered as suitable in the climatic trend analyses conducted in this study.

2.3. Generalized Additive Models

We employed generalized additive models (GAMs) to model the trends and the within year variation of the monthly time series data. GAMs are capable of modelling non-linear relationships between the response variable and the predictors [34] and have many applications in ecology and environmental sciences [35–37]. GAMs are also used in time-series analysis because they can effectively capture non-linear trends in time series and can also deal with the irregular spacing of samples in time. With GAMs, the components of a time series can be represented as smooth functions. The smooth functions are non-linear representations of the covariates which are composed by the sum of K simpler basis functions [36]. A general form of generalized additive model is:

$$g(Y) = \beta + f_1(x_1) + f_2(x_2) + \dots + f_n(x_n) \quad (1)$$

where Y is the expected response value, β is the model intercept, and f_1, f_2, f_n are the smooth functions of the predictors x_1, x_2, x_n [38]. GAMs have several applications such as modelling high frequency water quality data [39]. Models were built using a trend term (named “Time”), a within year variation term (“Month”) and the interaction between “Time” and “Month”. For “Time” smooth term we used cubic regression smoothing spline while for “Month” we used the cyclic cubic spline with $k = 12$. The interaction smooth

term was defined with the *ti* function. To deal with the temporal residual autocorrelation we included an AR1 model. Finally, we added the Lake as a factor to produce smooths for each lake. GAMs were fitted with the *bam* function (which fits GAMs to very large datasets) with the “mgcv” package in R environment [40].

3. Results

3.1. Surface Temperature Time Series Analysis

The model for surface temperature has a high adjusted R^2 (0.967) and explains 96.8% of the total deviance. The significance of the smooth terms for each lake shows that the interannual trend and the effect of seasonality are highly significant ($p < 0.001$). All lakes have exhibited significant rising trends from 1981 to 2020 (Figure 2). The interaction term between time and season was not significant which implies that most likely warming did not vary significantly among seasons. Table 2 lists the mean, minimum, and maximum values of annual surface temperature per decade and it shows that temperature consistently increases for almost all lakes and also the magnitude of change since 1981. The average rates of annual temperature increase range from $0.33\text{ }^{\circ}\text{C decade}^{-1}$ for lake Trichonida to $0.55\text{ }^{\circ}\text{C decade}^{-1}$ for lake Doirani. In general, lakes situated at northern parts of Greece had higher rates of temperature increase per decade ranging between 0.46 and $0.55\text{ }^{\circ}\text{C decade}^{-1}$. Lakes that are located at southern Greece (e.g., Trichonida, Ozeros, Lysimachia, Stymfalia, Iliki) had lower rates of temperature increase ranging between 0.3 and $0.4\text{ }^{\circ}\text{C decade}^{-1}$. Overall, the average rate of annual surface temperature increase was $0.43\text{ }^{\circ}\text{C decade}^{-1}$.

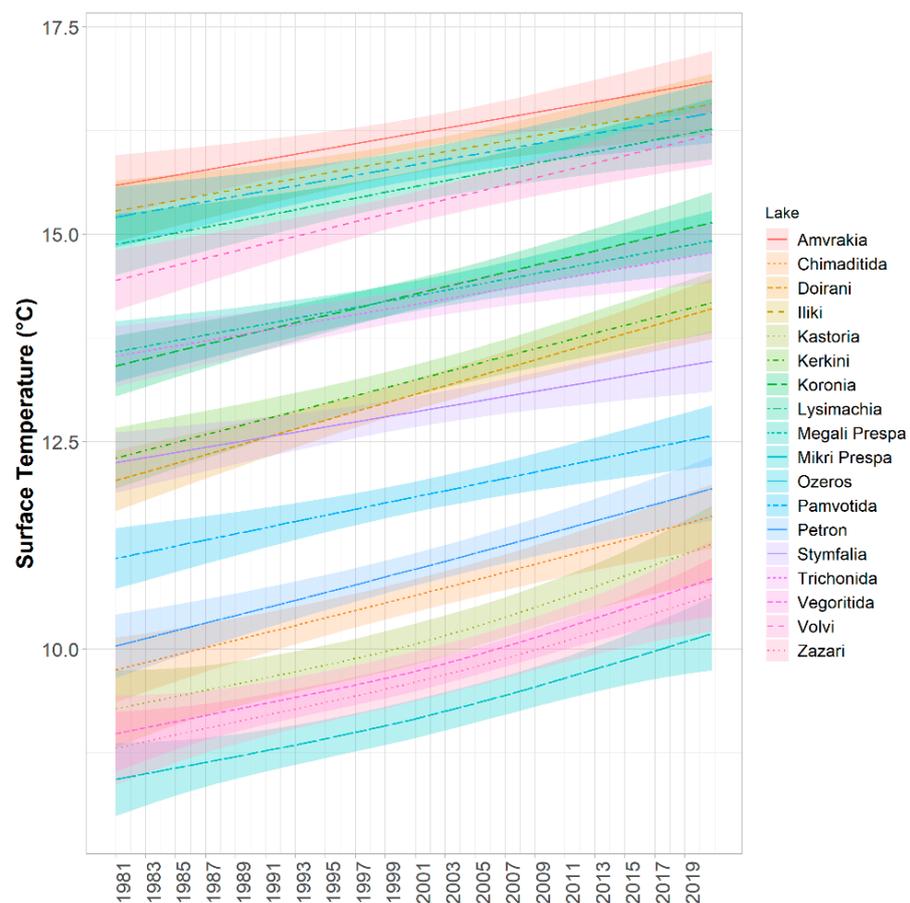


Figure 2. Monthly average surface temperature trends from 1981 to 2020 over 18 lakes of Greece. The shaded area represents the 95% confidence intervals.

Table 2. Mean, minimum, and maximum annual surface temperature (°C) over the 18 lakes per decade.

	1981–1990			1991–2000			2001–2010			2011–2020		
	Mean	Min	Max									
Doirani	12.42	11.39	13.48	12.74	11.82	14.15	13.13	12.51	14.14	13.92	13.25	14.64
Kerkini	12.67	11.89	13.56	12.93	12.15	14.23	13.27	12.62	14.06	14.01	13.19	14.64
Volvi	14.81	14.19	15.77	15.01	14.28	16.14	15.39	14.77	16.15	16.02	15.02	16.54
Koronia	13.77	13.19	14.68	13.98	13.19	15.14	14.31	13.71	15.02	14.98	13.93	15.44
Megali Prespa	13.89	13.39	14.46	13.93	13.18	15.11	14.33	13.66	14.94	14.76	14.14	15.27
Mikri Prespa	8.78	8.11	9.3	8.78	7.96	10.24	9.28	8.48	10.11	9.95	9.31	10.31
Vegoritida	9.31	8.54	10.11	9.43	8.37	10.9	9.81	8.8	10.93	10.58	9.78	11.16
Petron	10.43	9.37	11.39	10.62	9.48	12.22	11.01	9.96	12.31	11.72	10.95	12.33
Chimaditida	10.15	9.04	11.12	10.31	9.17	11.85	10.68	9.66	11.98	11.39	10.59	12.09
Zazari	9.17	8.05	10.15	9.28	8.11	10.81	9.66	8.65	10.92	10.39	9.62	11.07
Kastoria	9.68	8.65	10.49	9.64	8.48	11.12	10.22	9.3	11.31	10.96	10.12	11.51
Pamvotida	11.47	10.92	12.01	11.46	10.45	12.44	11.91	11.19	12.61	12.47	11.77	12.74
Amvrakia	15.91	15.35	16.55	15.91	15.01	16.89	16.26	15.68	16.78	16.69	16.09	17.24
Ozeros	15.52	15.02	16.12	15.53	14.71	16.47	15.9	15.3	16.47	16.32	15.7	16.83
Trichonida	13.85	13.34	14.39	13.85	13.05	14.83	14.22	13.53	14.76	14.64	13.99	15.03
Lysimachia	15.22	14.78	15.71	15.21	14.47	16.1	15.69	15.1	16.26	16.12	15.49	16.58
Iliki	15.57	14.92	16.42	15.66	14.91	16.51	16.05	15.39	16.98	16.38	15.23	16.99
Stymfalia	12.56	12.07	13.23	12.57	11.73	13.47	12.96	12.36	13.61	13.28	12.22	13.69

3.2. Precipitation and Wind Speed Modelling

The GAM for precipitation had a relatively low adjusted R^2 (0.445) and explained 45.8% of the deviance. Significant interannual trends were found for 14 out of the 18 lakes (Table 3, Figure 3). Lakes located at the western part of Greece (West of the Pindos Mountains) showed the most significant trends ($p \leq 0.005$). For the remainder lakes, trends were either insignificant (four lakes) or were less significant (p value ranging between 0.001 and 0.094). As expected, season was a highly significant term for all lakes ($p < 0.005$, Table 3, Figure 4). We also found that for four lakes located at the Southwestern Greece (Trichonida, Lysimachia, Amvrakia, Ozeros) the interaction term was significant ($p < 0.01$). The shape of the precipitation trend over time varies among the lakes (Figure 3). In some cases, there is a clear small rising trend but for most lakes the trend follows a complex shape where precipitation decreases till the early 1990s, it increases until early 2010s to decline again until 2020. This complex type of response is also shown from the mean values of annual precipitation for each decade (Table 4) where for the first two decades annual precipitation declines for all lakes but since 2000 there is a notable increase.

Table 3. Results of GAM modelling of monthly precipitation.

R-sq. adj	0.445	Deviance Explained	45.8%
Lake	Approximate Significance of Smooth Terms		
	s (Time)	s (Season)	ti (Time * Season)
Amvrakia	$p < 0.001$	$p < 0.001$	$p = 0.004$
Chimaditida	$p = 0.039$	$p < 0.001$	NS
Doirani	$p = 0.054$	$p < 0.001$	NS
Iliki	NS	$p < 0.001$	NS
Kastoria	NS	$p < 0.001$	NS
Kerkini	NS	$p < 0.001$	NS
Koronia	$p = 0.076$	$p = 0.008$	NS
Lysimachia	$p = 0.001$	$p < 0.001$	$p < 0.001$
Megali Prespa	$p = 0.065$	$p < 0.001$	NS
Mikri Prespa	$p = 0.070$	$p < 0.001$	NS
Ozeros	$p = 0.001$	$p < 0.001$	$p = 0.008$
Pamvotida	$p < 0.001$	$p < 0.001$	NS
Petron	$p < 0.001$	$p < 0.001$	NS
Stymfalia	$p = 0.044$	$p < 0.001$	NS
Trichonida	$p = 0.005$	$p < 0.001$	$p = 0.001$
Vegoritida	$p = 0.094$	$p < 0.001$	NS
Volvi	NS	$p < 0.001$	NS
Zazari	$p = 0.047$	$p < 0.001$	NS

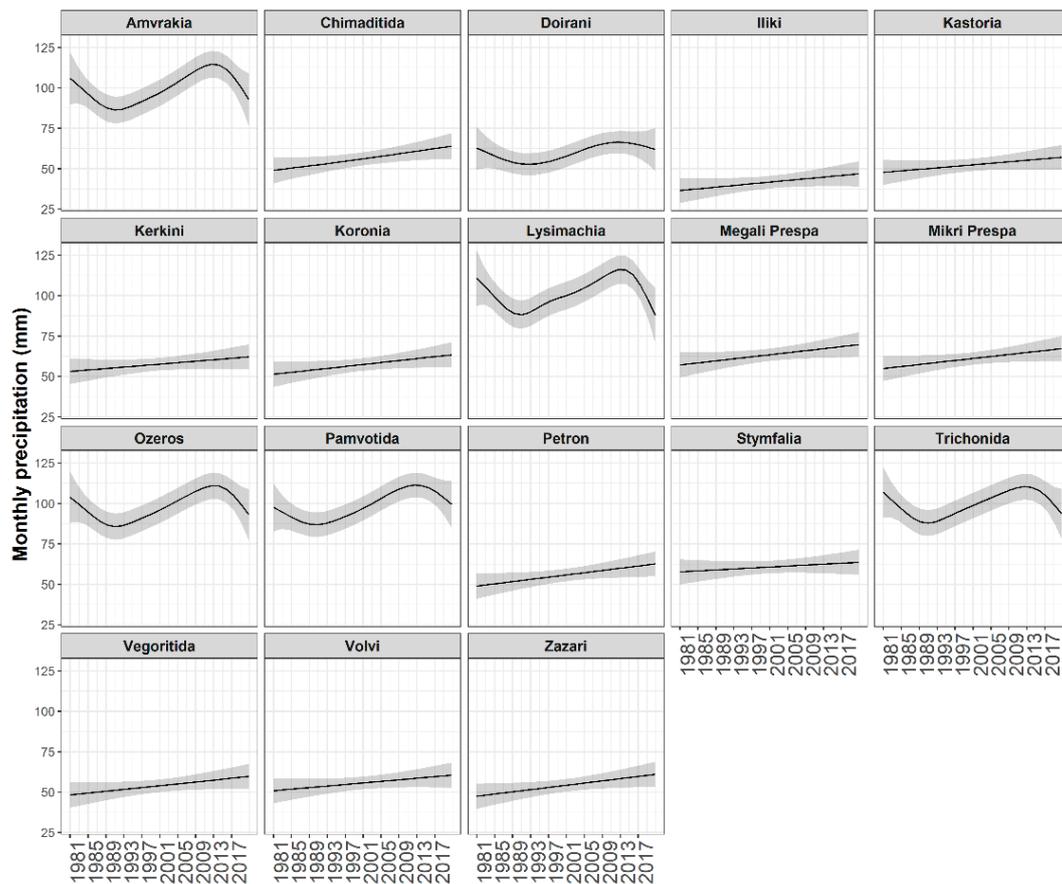


Figure 3. Monthly precipitation trends from 1981 to 2020 over 18 lakes of Greece. The shaded area represents the 95% confidence intervals.

Table 4. Mean, minimum, and maximum annual precipitation (mm) over the 18 lakes per decade.

	1981–1990			1991–2000			2001–2010			2011–2020		
	Mean	Min	Max									
Doirani	688	515	882	627	431	843	793	558	1071	774	452	1128
Kerkini	668	518	837	629	387	871	745	506	887	736	425	1053
Volvi	631	468	932	622	422	769	722	455	923	703	553	924
Koronia	647	491	912	628	426	770	747	535	923	743	568	1014
Megali Prespa	714	577	893	711	548	903	816	607	1062	818	638	1055
Mikri Prespa	689	544	858	682	513	864	785	581	1006	790	619	1009
Vegoritida	608	477	763	590	429	724	692	500	875	714	605	830
Petron	624	495	751	607	452	738	711	517	927	751	627	865
Chimaditida	624	485	749	610	465	750	716	520	939	765	638	912
Zazari	604	467	733	593	448	736	691	499	891	729	604	880
Kastoria	588	455	722	596	413	761	664	486	845	682	547	792
Pamvotida	1082	883	1385	1102	861	1461	1287	965	1964	1300	855	1540
Amvrakia	1143	971	1418	1081	767	1433	1269	950	1714	1325	823	1721
Ozeros	1123	905	1136	1073	755	1425	1256	945	1610	1306	867	1705
Trichonida	1150	931	1493	1100	781	1423	1283	883	1665	1296	899	1588
Lysimachia	1182	960	1497	1114	793	1446	1307	927	1739	1336	845	1694
Iliki	448	277	571	465	255	599	536	369	676	555	374	740
Stymfalia	703	506	825	699	529	814	753	558	1012	773	642	1019

For wind speed the GAM had a similar adjusted R^2 with the precipitation (0.449) explaining 46.2% of the total deviance. Yet, the trends over time were significant in just two occasions (lakes Iliki and Koronia) but there was a significant seasonal effect on the wind

speed for all lakes. The interaction effect was insignificant for all lakes. With the exception for Iliki where wind speed has increased notably (Figure 5), there is not any obvious trend for the rest of the lakes. In fact, it seems that monthly wind speeds remain stable during these four decades.

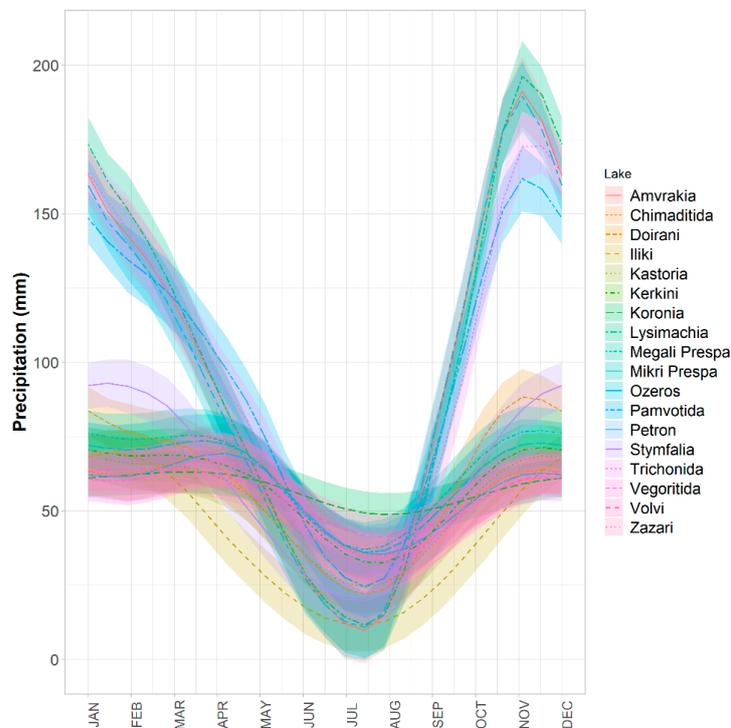


Figure 4. Modelled monthly variation of precipitation among the 18 lakes. The shaded area represents 95% confidence intervals.

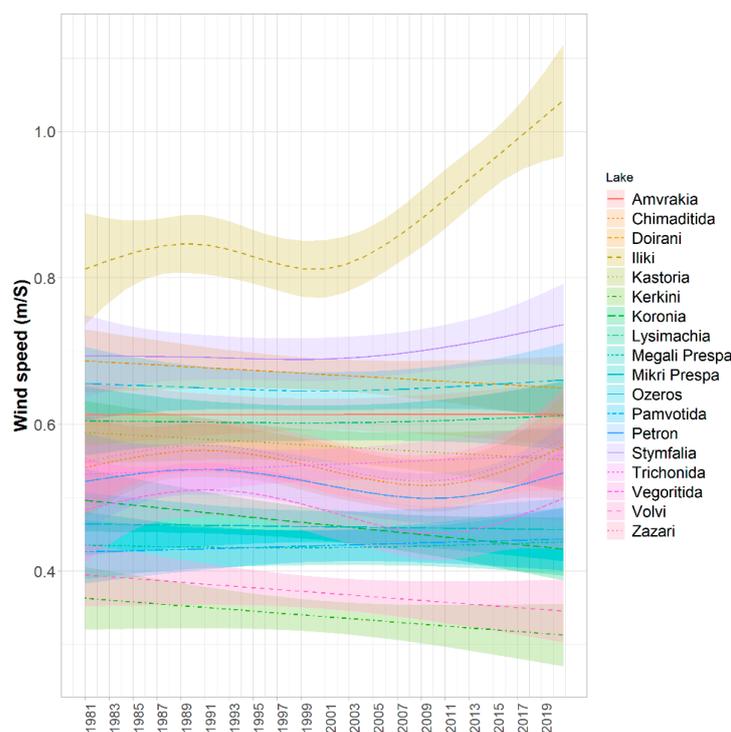


Figure 5. Monthly average wind speed trends from 1981 to 2020 over 18 lakes of Greece. The shaded area represents the 95% confidence intervals.

4. Discussion

4.1. Significant Changes of Climatic Variables

We showed that all lakes have exhibited a clear rising trend of surface temperature which corroborates similar findings from many other studies. For instance, a global scale analysis of lake surface water temperatures reported an average rate of lake surface water temperature increase of $0.31\text{ }^{\circ}\text{C decade}^{-1}$ [4]. Other studies conducted at a regional or local scale have also shown a significant temperature increase with subsequent implications for the lake structure and functioning [41–45]. In our case, the average annual surface temperature increase was $0.43\text{ }^{\circ}\text{C decade}^{-1}$. This rate is close to the average rate of surface skin temperature increase for the Northern hemisphere, that is $0.49\text{ }^{\circ}\text{C decade}^{-1}$, estimated from satellite measurements for a period of approximately 13 years [46]. Sobrino et al. [47] also estimated high rates of land surface temperature increase (average $0.36\text{ }^{\circ}\text{C decade}^{-1}$) for the Northern hemisphere at latitudes 23.5° – 66.5° , using satellite products for the period 2003–2016. Another study by Lieberherr and Wunderle [48] examined specifically the lake surface temperature trends for several European lakes for a period of 36 years and found that lake warming trend ranges from 0.2 to $0.8\text{ }^{\circ}\text{C decade}^{-1}$ with higher rates estimated for higher latitudes. The same paper documents an increasing trend for lake Trichonida of $0.21\text{ }^{\circ}\text{C decade}^{-1}$, which is albeit lower than our estimation of $0.33\text{ }^{\circ}\text{C decade}^{-1}$. This is probably due to the method of trend estimation since Lieberherr and Wunderle calculated the non-parametric Thiel–Sen slope, whereas we estimated slopes derived by linear trends. Overall, our results are in line with studies that have reported high warming rates in the last four decades. Interestingly enough, studies that have investigated warming rates for larger time spans (e.g., since early 20th century or 1960s) have noted lower rates of surface temperature increase [49]. Thus, most of the lake warming has occurred since 1980s, that is the time period studied in our paper. With regard to precipitation, we found more complex trends and overall, it appears that annual and average monthly precipitation has remained stable. Although there is a general consensus that rainfall declines in the Mediterranean, however, we did not find such a trend [16,50]. However, studies focused on Greece using historical long-term data have suggested that the trajectories of change depend on the spatial and temporal scale [21]. Thus, many regions of Greece have shown a decline in rainfall from 1950s to 1980s, but since 1980s rainfall increased and remained stable [21,51]. This pattern resembles our findings as we also noted that for certain lakes precipitation has decreased until 2000 and then increased. Besides, for most lakes we found a slight rising trend from 1980s which corroborates the findings of Markonis et al. [21]. However, the GAM explaining the observed precipitation trends had a relatively low adjusted R^2 and thus the results should be treated with caution. Still, these results do not imply that areas in Greece are not becoming drier, since the combination of extreme summer heatwaves and heavy autumn precipitation indicate an increase of droughts [17,50]. In practice, the decreased winter precipitation, the rising temperatures, and the increased droughts offset the increased rainfall during heavy events. With this regard, future research could focus on evaluating evapotranspiration trends over lakes in order to examine whether the impact of climate change has affected the hydrology and the water level. This is particularly important for lakes in the Mediterranean which have shown significant water level changes associated with climatic changes [9,27,52].

Another interesting finding concerns the fact that we did not find any significant change of average monthly wind speeds although there are reports of land wind speed declining globally over the past few decades [11,53,54]. This observation has raised particular interest among lake scientists because recent evidence show that atmospheric stilling, that is the global decline in annual wind speed, may lead to prolonged thermal stratification and affect the production of phytoplankton in certain lakes [8,55]. Perhaps examining wind speeds at a finer temporal scale (e.g., on daily basis) may reveal significant changes in wind dynamics, for instance an increase or decrease of the frequency of extreme winds, that could influence lake mixing and phytoplankton productivity. Undoubtedly, delineating

the effect of wind speed on limnological processes may prove a complex task [22] even for cases where a declining trend has been documented.

4.2. Implications for Limnological Processes

Lake scientists and other environmental scientists often attempt to relate their scientific findings with the ongoing climate change. Yet, for many regions of Europe, and elsewhere, the lack of specific evidence that quantify the magnitude of change urge the scientists to make assumptions or to use more generalized estimations of the climate change in order to discuss their results.

To this end, this study documents the climatic change that has occurred at the wider environment of 18 important lakes of Greece during the last forty years. Thus, it provides a good estimation of how much the lake surface temperature has increased and shows that precipitation exhibits a more complex interannual trajectory which varies among the different regions of Greece. These findings are important because it can help scientists to better understand the impact of climate change on the lake ecology and other processes such as eutrophication.

For instance, lake warming may explain the increase in the occurrence of toxic cyanobacteria blooms that has been already reported for several lakes in Greece [56–60]. Rising temperature may enhance the cyanobacteria growth rate but also may increase the duration of the lake stratification which favors the buoyant cyanobacteria [61]. A study of 2005 by Vardaka et al. [56] reported 18 new species of cyanobacteria for nine lakes of Greece compared to previous studies that were conducted in the 1980s and 1990s. Many of these species produce toxins and were dominant. Besides excessive nutrients, warming is considered a key driver of increased probability of harmful algal blooms and elevated concentrations of microcystin [62,63]. Gkelis et al. [64] found that microcystin concentration correlated positively with temperature in a shallow eutrophic lake of Greece. Naturally, warming is a key driver of eutrophication and not only cyanobacteria [65], but because some cyanobacteria might produce toxic substances, limnologists and freshwater biologists are particularly worried about the increased risk of harmful algal blooms. Still, eutrophication persists as a major issue in many areas worldwide which is connected with many other serious problems for the aquatic biota. Because the effect of warming on phytoplankton biomass depends on the lake trophic state, phytoplankton-rich lakes are more likely to present higher phytoplankton biomass in the future whereas in phytoplankton-poor lakes biomass will decrease [66]. In fact, there are many other possible implications of lake warming on aquatic food webs and communities that scientists have only recently started to explore [67,68]. For example rising water temperatures seem to be a key factor for reconstructing planktonic food webs [41,69].

As we did not identify very strong interannual trends for precipitation and wind speed we presume that these two climatic variables had a very small role in shaping the structure and functioning of the examined lakes through the last forty years. Still, examining changes in the frequency of events of extreme precipitation or wind speed could reveal significant effects on lake ecology. For instance, a documented increase of the frequency of extreme weather events is related to big changes of lake phytoplankton communities [10]. These effects depend on the adjacent land uses and other catchment characteristics since the extreme weather events (i.e., storms) influence runoff and subsequent sediment and nutrient loading. Furthermore, in terms of prospects for future research, reconstruction of climatic variability based on lake sediment cores could be extremely useful for the validation of climatic trends obtained by modelled or climate reanalysis data [70,71]. Based on the results from previous studies on the lakes, we know that land use changes and intensification of anthropogenic intervention (e.g., agriculture, urbanization, pollution) have been a key driver of lake-related changes [27,52,72]. Thus, from a management perspective, it is crucial to investigate the combined effect of extreme weather events and anthropogenic land use changes on lake ecosystems. Temperature on the other hand, must

have had a strong influence as the obvious increase in all lakes could amplify the effect of eutrophication and other human-induced changes.

5. Conclusions

In summary, this study provides evidence of the climate change that has occurred at the environment of 18 lakes of Greece that consist important areas of biodiversity conservation. The model for explaining temperature trends had a high adjusted R^2 , whereas the models for precipitation and wind speed explained a rather moderate amount of the total deviance. We found clear signs of lake warming as all lakes showed increasing surface temperatures from 1981 to 2020. In several cases the rate of annual surface temperature increase was more than $0.43\text{ }^\circ\text{C decade}^{-1}$ which is close to the average rates reported for the Northern hemisphere. We also showed that precipitation has a more complex interannual trend and that during the last four decades the overall change is small. However, examining seasonal shifts in rainfall may be more useful for assessing the impact on the lake ecosystem. Finally, we did not ascertain a decline in the wind speed, as several studies have recently reported from regions worldwide. Yet, our results are significant, particularly for lake scientists, because they can use them to associate the changes in the climate with changes that have occurred in the ecology of the lakes during the past few decades.

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