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ORIGINAL ARTICLE

An integrated assessment of climate change impacts for Greece in the near future

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Abstract Climate changes in the Mediterranean region, related to a significant increase in temperature and changes in precipitation patterns, can potentially affect local economies. Agriculture and tourism are undoubtedly the most important economic sources for Greece and these may be more strongly affected by changing future climate conditions. Climate change and their various negative impacts on human life are also detected in their environment; hence this study deals with implications, caused by changing climate, in urban and forest areas. Potential changes for the mid-twenty-first century (2021–2050) are analysed using a high-resolution regional climate model. This paper presents relevant climatic indices, indicative for potential implications which may jeopardise vital economic/environmental sectors of the country. The results provide insights into particular regions of the Greek territory that may undergo substantial impacts due to climate change. It is concluded that the duration of dry days is expected to increase in most of the studied agricultural regions. Winter precipitation generally decreases, whereas an increase in autumn precipitation is projected in most areas. Changing climate conditions associated with increased minimum temperatures (approximately 1.3°C) and decreased winter precipitation by 15% on average suggest that the risk for forest fires is intensified in the future. In urban areas, unpleasantly high temperatures during day and night will increase the feeling of discomfort in the citizens, while flash floods events are expected to occur more frequently. Another impact of climate change in urban regions is the increasing energy demand for cooling in summer. Finally, it was found that continental tourist areas of the Greek mainland will more often face heatwave episodes. In coastal regions, increased temperatures especially at night in combination with high levels of relative humidity can lead to conditions that are nothing less than uncomfortable for foreigners and the local population. In general, projected changes associated with temperature have a higher degree of confidence than those associated with precipitation.

Keywords Greece · Climate change · Impacts · Forestry · Agriculture · Urban areas · Tourism

Introduction

The Mediterranean region is vulnerable to climate change particularly due to its sensitivity to drought and rising temperatures (IPCC 2007a; Giorgi 2006; Gao and Giorgi 2008). Climate change is related not only to changes in the mean climate but also to changes in the frequency and intensity of extreme climate events (Kostopoulou and Jones 2005; Alpert et al. 2008). These changes may adversely affect vital economic sectors, such as agriculture and tourism, and have substantive impacts on local communities. In addition, extreme climate events can be harmful to human health (Patz et al. 2005), while climate change may also have a direct impact on local people's

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lives as it affects sectors such as water resources and energy (Henderson and Muller 1997; Subak et al. 2000; Körner et al. 2005; Giannakopoulos et al. 2009a). For all these reasons, in recent years, the scientific community has developed a special interest in studying potential future climate changes. In this study, an attempt is made to investigate potential implications of climate change in the near future (2021–2050) in Greece.

In 2007, the total population of Greece was approximately 11.19 million inhabitants, according to the data provided by the National Statistical Service of Greece. According to the Census of March 2001, the total population of the country was approximately 10.95 million. The total population increased by 9.1% compared with the 1991 Census results, with 34% of the total population living in the greater Athens area. The average size of households has decreased (2.80 persons per household according to the 2001 Census) while population density is 85.2 inhabitants/km^2. Greece has a total area of 131,957 km^2 and occupies the southernmost extension of the Balkan Peninsula. The mainland accounts for 80% of the land area, with the remaining 20% divided among nearly 3,000 islands. The Greek landscape, with its extensive coastline, exceeding 15,000 km in length, is closely linked to the sea, since only a small region in the northwest is further than 80 km from the sea. Approximately 25% of it is lowland, particularly the coastal plains along the seashore of the country. Forest land, including forests and other wooded lands (branchy dwarf trees and scrubs), covers 49.4% of the total area of the country. Grassland, rangeland and pasture with vegetation that cannot be classified as forest, covers 13% of the total area of the country. Agricultural land, including fallow land, accounts for 29.2% of the total area. Settlements, developed land including transportation infrastructure and human settlements of any size, account for 4.0% of the total area. Finally, wetlands, land that is covered or saturated by water for all or the greatest part of the year, and other land, areas that do not fall into any of other land-use categories (e.g. rocky areas, bare soil, mine and quarry land), account for 2.3 and 2.0% of the total area, respectively. Greece has a typical Mediterranean climate with mild and wet winters in the southern lowland and island regions and rather cold winters with strong snowfalls in the mountainous areas in the central and northern regions and hot, dry summers (HMSO 1962; Bolle 2003). During winter, the coldest period is between January and February with the mean minimum temperature ranging between 5 and 10°C near the coast and 0–5°C over the mainland with the northern areas exhibiting even lower temperatures (below freezing). Except for a few thunderstorms, rainfall is rare from June to August, and days are mainly sunny and dry with mean maximum temperatures ranging between 29 and 35°C. The dry, hot weather is often relieved by a system of seasonal breezes.

Agricultural, forest, urban and touristic areas are selectively examined to estimate future climate change impacts. In order to achieve this, the Greek region was divided into sub-regions which are considered vulnerable to climate events such as extreme temperatures, droughts, floods or forest fires. Subsequently, several climate indicators, associated with extreme climatic events, were calculated for each selected area. The impacts of climate changes are expected to be more closely related to changes in the frequency of extreme climate events than to changes in mean conditions. This is partially attributed to the fact that a change in the 'mean' climate could cause disproportional changes in the extreme climate events.

Records from the National Statistical Service of Greece were utilized in order to set criteria and then select the 10 representative sub-regions for each economic sector in question. In particular, the urban regions research focused on the 10 largest Greek cities based on their population size. Regarding the agricultural regions, the 10 regions occupying the largest numbers of agricultural workers were selected. The 10 most important Greek tourist destination sites were defined according to the official accommodation capacity (higher number of beds available). Finally, the 10 largest natural conservation parks in Greece were studied.

Model data and methods

Daily output data, from the RACMO2 regional climate model (RCM), developed at KNMI in the Netherlands (Lenderink et al. 2003, 2007), developed within the framework of the ENSEMBLES project (http://www.ensembles-eu.org) and were used. RACMO2 has 40 vertical levels in a hybrid sigma-pressure following coordinate system. The horizontal resolution is 25 km × 25 km, which produces a European–Mediterranean grid of 85° longitude by 95° latitude grid cells in a rotated latitude–longitude projection. The model uses initial and boundary conditions from the General Circulation Model (GCM) ECHAM5. The high spatial resolution of RACMO2 enables a satisfactory representation of the sea area and the islands. The control run represents the base period 1961–1990 and is used here as reference for comparison with future projections for the period 2021–2050. The future period simulations of the model are based on the IPCC SRES A1B scenario (Nakicenovic et al. 2000). The A1B scenario provides a good mid-line scenario for carbon dioxide emissions and economic growth (Alcamo et al. 2007). The future period has been chosen specifically for the needs of stakeholders and policy makers to assist their planning in the near future, instead of the end of the twenty-first century as frequently used in other climate impact studies.

Apart from climatic indices employing directly temperature and precipitation as variables, we have also used more compound indices to represent future tendencies for sectors such as heat impact on human comfort, energy demand and forest fire risk. Heat impact on human comfort (or discomfort) is assessed by computing humidex (Masterton and Richardson 1979), a parameter employed to express the temperature perceived by people. Humidex is applied in summer and generally warm periods and describes the temperature felt by an individual exposed to heat and humidity. More specifically, the humidex parameter (in °C) is calculated by the following equation:

$$T\,(h) = T\max + 5/9 * (e - 10),$$

where e is the vapour pressure (6.112 * 10^(7.5 * Tmax/(237.7 + Tmax)) * h/100), Tmax is the maximum 2 m air temperature (°C) and h is the humidity (%).

Furthermore, 6 classes of humidex ranges are established to inform the general public for discomfort conditions (http://www.eurometeo.com/english/read/doc_heat):

- <29°C comfortable
- 30–34°C some discomfort
- 35–39°C discomfort; avoid intense exertion
- 40–45°C great discomfort; avoid exertion
- 46–53°C significant danger; avoid any activity
- >54°C imminent danger; heart stroke.

For energy, we have used the concept of Degree Days, which are defined as the difference (in °C) of mean daily temperature from a base temperature. This can be defined here as the difference of mean daily temperature from a threshold or base temperature at which energy consumption is at a minimum. During the warmer part of the year, temperatures commonly exceed a base temperature above which cooling is activated. By accumulating the daily exceedances during a given period, an indication of total energy demand can be estimated for that period (Cooling Degree Days or CDD). Similarly, the sum of daily temperature departures below a temperature threshold is a useful proxy for heating demand in the colder part of the year (Heating Degree Days or HDD). For the calculation of the HDD and CDD indices, the following equations were used:

$$\mathrm{HDD}i = \max(T^{*} - Ti, 0)$$
$$\mathrm{CDD}i = \max(Ti - T^{**}, 0)$$

where T* and T** are the base temperatures for HDD and CDD, respectively, In the present study, we use 15°C as the base temperature for estimating HDDs and 25°C as the corresponding threshold for CDDs, as used in the study of Giannakopoulos et al. (2009a, b).

The risk of fire due to extreme meteorological conditions has been assessed using the Canadian Fire Weather Index (FWI). The FWI is a numerical rating of fire's intensity and is used to estimate the difficulty of fire control. FWI requires the calculation of daily maximum temperature, relative humidity, wind and precipitation and is described in detail in van Wagner (1987). Briefly, it consists of six components that account for the effects of fuel moisture and wind on fire behaviour. These include numeric ratings of the moisture content of litter and other fine fuels, the average moisture content of loosely compacted organic layers of moderate depth, and the average moisture content of deep, compact organic layers. The remaining components are fire behaviour indices, which represent the rate of fire spread, the fuel available for combustion and the frontal fire intensity; their values rise as fire danger increases. Although FWI has been developed for Canadian forests, several studies have shown its suitability for the Mediterranean basin (Moriondo et al. 2006; Good et al. 2008). FWI is divided into four fire danger classes:

- Low 0–7
- Medium 8–16
- High 17–31
- Extreme >32.

Each annual parameter is calculated from the RCM daily output and then averaged for both the control (1961–1990) and the future period (2021–2050). For spell type parameters (e.g. max length of summer days, max length of dry spell <1 mm), the annual longest spell is calculated for each year and then averaged over both the future and the control period.

It should be noted that climate projections are associated with uncertainties. Uncertainties begin with different socioeconomic assumptions that affect projections of greenhouse gas emissions (GHG), and flow through differing potential emission scenarios and ranges of GHG concentrations, radiative forcing, climate system responses and feedbacks. An attempt to quantify uncertainty is made by bootstrapping the 30-year differences of each parameter between the two periods (Mudelsee and Alkio 2007). Bootstrap works with artificially produced, (by means of a random number generator) resamples of the annual difference parameter sample. In our study, each sample consists of 30 values which are resampled 1,000 times with replacement. In each resample, the method calculates the mean of each sample and the 95th percentile confidence intervals are then computed from the resulting series. Thus, in the analysis performed, each mean parameter change is presented with a (±α) value which represents the confidence range value to add or subtract from the mean difference to get the limits. This is used as a measure to assess confidence in our results.

Results and discussion

Agriculture

A comprehensive analysis of climatic parameters associated with agricultural and water demand needs such as mean precipitation and drought duration are presented for the 10 most important agricultural areas in Greece, shown in Table 1. Changes in the number of wet and dry spells, drought duration as well as changes in growing season length have been investigated. Such changes should be very important to assess possible future water-shortages over the region and to provide a basis for associated impacts on the agricultural sector. Substantial changes in some of these indices exhibit significant environmental implications in the domain of study. For example, increasing trends in the number of consecutive dry days can be indicative that the problem of drought and desertification gets intensified. Desertification means land degradation in arid, semi-arid and dry sub-humid areas, resulting from a combination of climate effects (persistent hot and dry conditions) and human activities (overcultivation, overgrazing, deforestation and poor irrigation practices).

Regarding the agricultural areas in Greece as shown in Table 1, we present an analysis of climate change indicators with specific relevance to agriculture. More specifically, Fig. 1a presents changes in the maximum length of dry spell (i.e. spell where precipitation is less than 1 mm per day) between future (2021–2050) and present (1961–1990) periods for the examined agricultural regions in Greece. Open squares are drawn on the map to designate the ten examined agricultural regions. The numbers enclosed in the squares correspond to the regions as listed in ascending order in Table 1. Small increases of around 10 days appear in the agricultural areas of Achaia, Ilia, Aitoloakarnania to the west of the country. Larissa, Serres and Iraklio present an increase of around 15 days, whereas Fthiotida, Pella, Messinia and Evia show increases of 20 days. The confidence range values of these changes are as big as the changes implying large uncertainties, resulting from the episodic nature of precipitation affecting dry spell length.

Figure 1b illustrates potential future changes in the number of days, where maximum temperatures exceed 35°C. Under such temperature conditions, the productive stage of crops may be unfavourably affected. This parameter tends to increase in all selected agricultural areas. As expected, the inland areas in Larissa exhibit large changes that reach 20 additional hot days. Modest changes of 10–15 additional days occur in the remaining areas with the confidence range varying from ±3 to ±7 days.

In Fig. 1c, changes in the number of frost nights are shown. This is a very important factor for agricultural areas, especially where sensitive crops exist, such as orange and lemon groves. Reductions in the order of more than 15 days are evident in Pella and Serres, followed by 10 days in Larissa, Achaia and Fthiotida. Small reductions occur in the other examined regions, although it should be pointed out that they do not experience many frost nights even at the present period. Uncertainty estimates for this parameter range from ±2 to ±7 days.

Another important parameter for agricultural areas is the length of the growing season, i.e. the season with favourable conditions for crop growth. In Fig. 1d, changes in growing season length, defined as the changes in the number of days between the last day of spring frost and the first day of autumn frost, are presented. In general, crop growing season length increases in all selected agricultural areas as a result of the earlier ending and later starting frosts of spring and autumn, respectively. Small increases

Table 1 The top ten areas selected for study for each examined sector

	Agricultural area	Population of workers	Conservation park	Hectares	Urban area	Population	Tourist area	No of beds
1	Iraklio	79,182	Vikos-Aoos (Ioannina)	9,300	Inner Athens	789,166	Dodecanese	120,768
2	Aitoloakarnania	71,635	Prespes (Florina)	4,900	Thessaloniki	385,406	Attica	63,749
3	Messinia	53,236	White Mountains (Chania, Crete)	4,850	Patras	17,1616	Iraklio	63,484
4	Larissa	50,459	Olympos (Pieria)	3,988	Iraklio	142,112	Chalkidiki	59,882
5	Ilia	48,662	Parnitha (Attica)	3,812	Larissa	132,779	Cyclades	50,500
6	Achaia	47,561	Pindos (Ioannina)	3,534	Volos	85,001	Corfu	46,182
7	Evia	44,710	Parnassos (Viotia, Fokida)	3,513	Ioannina	75,550	Chania	34,452
8	Serres	43,249	Iti (Fthiotida)	3,010	Kavala	63,572	Rethymno	29,329
9	Fthiotida	42,809	Ainos (Cephalonia)	2,862	Lamia	62,452	Pieria	29,192
10	Pella	41,166	Sounio (Attica)	2,750	Kalamata	61,373	Zante/Cephalonia	37,586

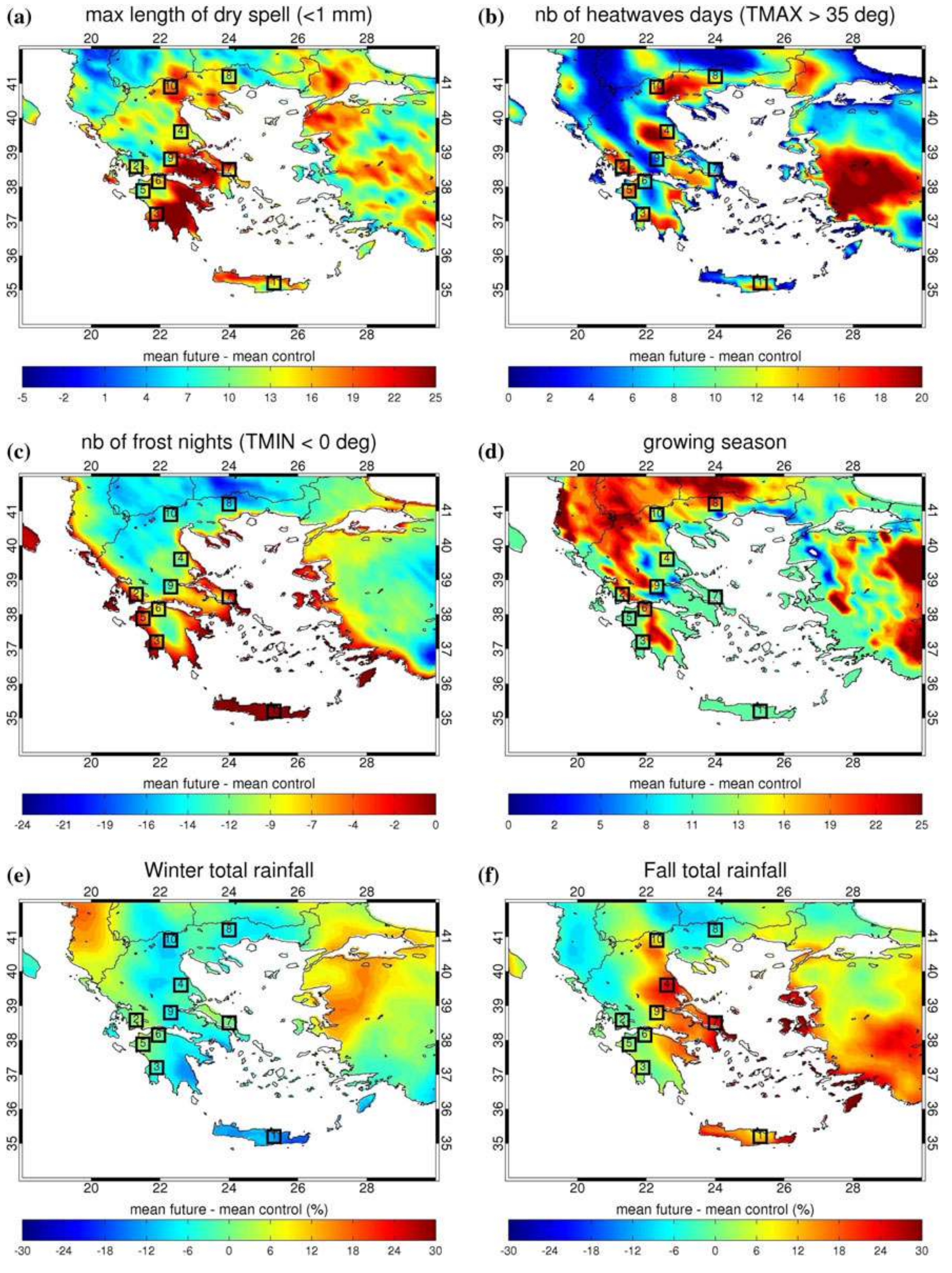

Fig. 1 Changes in **a** the maximum length of the dry spell, **b** the number of heatwave days, **c** in the number of frost nights **d** growing season length, **e** winter total precipitation (%), **f** autumn total precipitation (%) between 2021–2050 and 1961–1990 1990 for the selected agricultural regions of Greece

of 10 days are shown for the regions of Iraklio, Messinia, Ilia and Evia, whereas the increase for Larissa, Fthiotida and Pella reaches 15 days. Higher increases of about 20 days are revealed in Aitoloakarnania, Achaia and Serres. The confidence range for the growing season estimates varies from ±2 to ±7 days.

The percentage changes in seasonal precipitation for the selected agricultural regions in Greece were calculated and their patterns found different from season to season. Winter and autumn seasons are discussed since Greek agriculture strongly relies on autumn and winter rainfall. Additionally, it is important to note that these seasons exhibit contradictory patterns of change in seasonal precipitation. It is evident from Fig. 1f that winter precipitation decreases in the selected agricultural areas with more substantial decreases of 15% occurring in the areas of Serres, Pella and Iraklio. The other areas show decreases of around 10%. It is noteworthy, however, that these changes are associated with large uncertainties, bigger than the changes themselves.

Figure 1e indicates that the percentage changes in autumn precipitation are different from those in winter. In many of the agricultural areas, an increase in precipitation is projected. More specifically, the areas of Larissa and southern Evia will experience increases of up to 20%, whereas Pella and Iraklio will see increases of around 15%, followed by Fthiotida with a 10% increase. The remaining areas will not experience any changes in autumn precipitation. The 95th percentile confidence range in these projections ranges from 30 to 50%. In the other seasons (not shown), reductions similar to winter are projected but to a lesser degree. The general picture results in small overall reductions in annual precipitation for all areas. The overall findings of the analysis regarding agricultural Greek areas are summarized in Table 2.

Forestry

Mediterranean forests are regularly subjected to a large number of fires. An average of 50,000 fires sweep away from 700 × 10^3 to 1,000 × 10^3 ha of Mediterranean forests per annum (FAO 2007), causing enormous economic and ecological destruction. In particular, according to the average burnt area per fire, Greece has the most severe forest fire problems among the European Union countries (EU 2001). It has been estimated that the average area burnt per fire was 39.4 ha in Greece, 28.47 ha in Spain, 19.74 in Italy and 15.29 in Portugal (Iliadis et al. 2002). The destruction of forests is of great concern, since it might lead to many ‘side effects’, such as floods, soil erosion and consequent loss of fertility. Furthermore, forest fires play a fundamental role in determining the net carbon balance of the forest. Thus, they may affect greenhouse gas emissions with consequent direct repercussions on climate change. Forest fires, as any other ecosystem process, are highly sensitive to climate change because fire behaviour responds immediately to fuel moisture (Weber and Flannigan 1997; Stocks et al. 2001), which is affected by precipitation, relative humidity, air temperature and wind speed. Thus, the projected increase in temperature will increase fuel dryness and reduce relative humidity and this effect will worsen in those regions where rainfall decreases. Accordingly, increases in climate extreme events are expected to have a great impact on forest fire vulnerability (Beniston 2003; Körner et al. 2005).

A comprehensive analysis of climatic parameters with direct or indirect implications for forested areas has been undertaken for the most important natural conservation areas in Greece. These areas together with their occupied area in hectares appear in Table 1. Subsequently, a set of graphs presents an analysis of climate change indicators with specific relevance to forestry. The plots display the changes between the future (2021–2050) and the present (1961–1990) period. Both mean and extreme parameters are investigated.

The changes in average winter minimum temperature are shown in Fig. 2a. Increases in this parameter may affect forests, accustomed to colder conditions. If conditions become unbearable for them, forests may disappear from a

Table 2 Potential future changes in climate indices with particular relevance to agriculture

Area	Max dry spell length (days)	Days >35°C	Frost nights	Growing season (days)	Winter precip (%)	Autumn precip (%)
Iraklio	(+)15	(+)10	(−)5	(+)10	(−)15	(+)15
Aitol/nia	(+)10	(+)15	(−)5	(+)20	(−)10	–
Messinia	(+)20	(+)15	(−)5	(+)10	(−)10	–
Larissa	(+)15	(+)20	(−)10	(+)15	(−)10	(+)20
Ilia	(+)10	(+)15	(−)5	(+)10	(−)10	–
Achaia	(+)10	(+)10	(−)10	(+)20	(−)10	–
Evia	(+)20	(+)10	(−)5	(+)10	(−)10	(+)20
Serres	(+)15	(+)15	(−)15	(+)20	(−)15	–
Fthiotida	(+)20	(+)15	(−)10	(+)15	(−)10	(+)10
Pella	(+)20	(+)15	(−)15	(+)15	(−)15	(+)15

The (+) indicates increase, while (−) indicates decrease

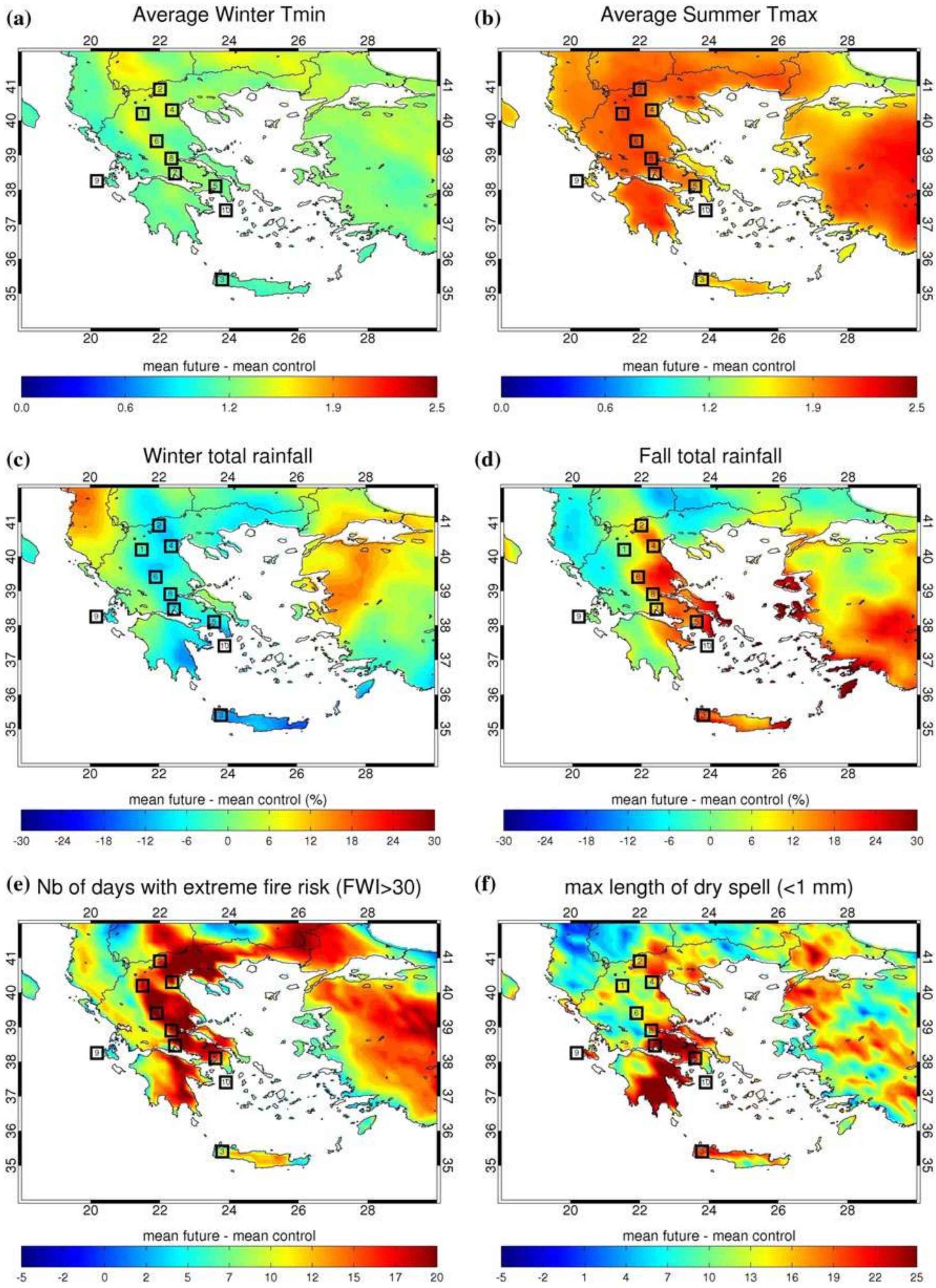

Fig. 2 Changes in **a** the average minimum winter temperatures, **b** the average maximum summer temperatures, **c** winter total precipitation (%), **d** in autumn total precipitation (%), **e** the number of days with extreme fire risk (FWI > 30), **f** the maximum length of the dry spell between 2021–2050 and 1961–1990 for the selected forestry regions of Greece

particular elevation and start to grow in higher altitudes. It becomes evident from Fig. 2a that most national conservation parks areas will experience a warming of about 1°C with confidence range values of around ±0.5°C. This warming will be greater in the areas of Vikos-Aoos, Pindos, Prespes, Parnassos and Olympos, reaching 1.3°C.

Figure 2b shows the changes in average summer maximum temperature. These plots indicate a greater increase in summer maximum temperatures compared with the winter minimum temperatures. The increase exceeds 1.5°C and in some cases reaches 2°C with confidence range values of around ±0.7°C. The most seriously affected areas are the national conservation parks in Vikos-Aoos, Pindos, Olympos, Iti and Prespes, which are in the interior of the country away from the sea influence. In contrast, areas affected by sea breezes show smaller changes. Such areas are the White Mountains in Crete, Ainos in Cephalonia and Sounio and Parnitha in Attica with confidence range around varying from ±0.5°C.

Changes in the hydrological cycle involving precipitation may have serious implications for the forests' sustainability. Figure 2c depicts changes in winter precipitation and it becomes clear that most of the national conservation parks undergo decreases. More specifically, decreases reach 15% for Olympos, White Mountains, Ainos and Prespes parks. Modest decreases that do not exceed 10% exist for Sounio, Parnitha, Iti and Parnassos. Vikos-Aoos area and Pindos are the only areas with no changes in winter rainfall patterns.

The autumn precipitation (Fig. 2d) reveals the reverse pattern compared with the one in winter. Areas that exhibit winter decreases show increases in autumn precipitation. In particular, a 15% or more increase in autumn precipitation is evident in Prespes, Olympos, Sounio, Parnitha, Parnassos and Iti. The White Mountains in Crete show a 10% increase. Conversely, Vikos-Aoos and Pindos parks will exhibit decreases in the order of 10%. No changes are projected for the Ainos park in Cephalonia. The confidence range values of these changes are bigger than the changes implying large uncertainties in precipitation modelling.

Regarding fire risk, as evidenced by Fig. 2e, most areas show increases in the number of days with extreme fire risk of the order of 10 days. Substantial increases of approximately 15 days will be evident in Iti and Parnitha whereas Ainos in Cephalonia has negligible changes (5 days increase) in fire risk occurrence. Uncertainties are smaller than the changes, implying a degree of robustness in the signal.

Regarding the maximum length of dry spell, as shown in Fig. 2f, the high mountain forest areas in the interior of the country, such as Olympos, Iti, Vikos-Aoos, Pindos reveal small increases of about 7 days. In the other parks (Parnitha, Prespes, Parnassos, Ainos, White Mountains), the increases are more significant and the maximum dry spell length increases by 15 days. Sounio shows a 7-day increase. The confidence range values of these changes are as big as the changes implying large uncertainties in precipitation affecting maximum dry spell length. The overall findings of the analysis regarding potential changes in Greek forestry due to a changing climate are summarized in Table 3.

Urban areas

Climate projections for the Mediterranean suggest that the region will become warmer and drier with more frequent and extreme weather events (Alcamo et al. 2007). This poses a significant threat to urban areas in the form of increased risks for flash floods and heatwaves. These climate hazards will inevitably aggravate other environmental issues, such as water resource availability, air pollution and peri-urban forest fire risk. Human health will be a major issue of concern under climate change together with the challenges of rising energy demand for cooling and shifts in the seasonal pattern of tourism. Vulnerability to climate change is greater for urban areas with limited economic

Table 3 Potential future changes in climate indices with particular relevance to forestry

	Winter min temps (^{o}C)	Summer max temps (^{o}C)	Winter precip (%)	Autumn precip (%)	Fire risk (days)	Max dry spell length (days)
Ainos	(+)1	(+)1.5	(−)15	–	(+)5	(+)15
Vikos-Aoos	(+)1.3	(+)2	–	(−)10	(+)10	(+)7
Pindos	(+)1.3	(+)2	–	(−)10	(+)10	(+)7
Olympos	(+)1.3	(+)2	(−)15	(+)15	(+)10	(+)7
Iti	(+)1	(+)2	(−)10	(+)15	(+)15	(+)7
Parnassos	(+)1.3	(+)1.5	(−)10	(+)15	(+)10	(+)15
Parnitha	(+)1	(+)1.5	(−)10	(+) 15	(+)15	(+)15
Sounio	(+)1	(+)1	(−)10	(+)15	(+)10	(+)7
Prespes	(+)1.3	(+)2	(−)15	(+)15	(+)10	(+)15
White Mountains	(+)1	(+)1.5	(−)15	(+)10	(+)10	(+)15

The (+) indicates increase, while (−) indicates decrease resources, rapid population growth and poor planning and regulation. Increased frequency of heatwaves and persistence of high temperatures are the key aspects of climate change common to all urban areas. Urbanization itself greatly affects surface characteristics and their interaction with the wider atmosphere. This leads to distinct urban climates that differ substantially from rural environments (Best 2005). The most apparent consequence of this is the urban heat island. The capacity for the built environment to store heat during the day and release it at night, along with the direct release of heat through human activity (for example, heating or cooling of buildings, traffic and human metabolism) can contribute to higher temperatures within cities compared with their rural surroundings. The urban heat island is also sensitive to the ambient weather and climate.

In an urban area study, an integrated approach is required across multiple temporal and spatial scales and sectors. In the spatial dimension, work needs to extend from the inner city boundaries to the surrounding mountains and forests. In the temporal dimension, research needs to range from the current observed time period (using available meteorological and sector data) to future time periods using data from several climate change projections. In addition, a multi-sector approach to climate change impacts has to be adopted. Impact sectors range from direct climate impacts on natural ecosystems (such as flash floods and forest fire risk) to indirect impacts, resulting from combined climate-social-economic linkages (such as energy demand, tourism and health). Furthermore, the dynamics of the climate system needs also to be examined in an integrated fashion. Regarding the ten largest cities in Greece as listed in Table 1, an analysis of climate change is undertaken based on climate indicators with specific relevance to urban areas. The plots display the changes between the future (2021–2050) and the present (1961–1990) period.

Changes in the number of days with temperature exceeding 35°C are expected to have an impact in population discomfort in the urban areas. From Fig. 3a, it is evident that this parameter increases in all selected Greek cities. The largest changes seem to occur in the cities of Thessaloniki, Patras, Kalamata, Larissa and Lamia where more than 20 hot days per year are expected. Modest changes appear in as Athens, Ioannina, Kavala and Volos with increases that do not exceed 15 days, whereas Iraklio in the island of Crete reveals even smaller increases of up to 10 days. Regarding this parameter, the influence of the nearby sea is playing a dominant role in tempering the fierce summer heat. The confidence range is of the order of ±4 days, implying that the signal of these changes is rather robust.

Another parameter very important for the urban areas is the change in the number of warm nights per year. We define these as nights where night-time temperature is above 20°C and characterize them 'tropical nights'. In addition, this parameter is closely associated with population health, since a 'tropical' night following a 'heatwave' day can lead to increased levels of population heat stress and discomfort. Figure 3b displays changes in this parameter for the selected urban sites in Greece. It becomes clear from this plot that tropical nights increase almost everywhere and it is interesting to note that coastal urban sites are more affected than continental cities. According to this figure, all selected urban sites except Ioannina will experience about an extra month per year of warm nights. In Ioannina, the increase will be less than 20 days, possibly due to the cooling effects of the mountain breezes, when cool air flows downslope from the nearby Pindos mountains. Uncertainties associated with this parameter are small since the confidence range varies from ±5 to ±8 days.

Apart from uncomfortable temperatures, flash flooding is another concern for people in urban areas and hence it is examined whether flash flooding can be exacerbated by climate change. To get some insight into this threat, the percentage changes in the amount of rainwater that falls in a short period of time (3 days in this case) within the year is calculated and presented in Fig. 3c. A tendency for this parameter to increase, in conjunction with a decrease in total annual rainfall, implies that potential events of excessive rain during short periods of time increase flash flood risk. Figure 3c presents a rather mixed pattern. Some Greek cities do not exhibit any substantial changes in this parameter, most notably Patras, Kalamata, Iraklio, Ioannina and Kavala, while other cities present increases. Particularly, in Lamia, the 3-day accumulated rainfall increases by 20%, while in Larissa and Volos by 15%. Smaller changes are noticeable in Athens and Thessaloniki with an increase of about 10%. It should be noted, however, that uncertainties are quite large since the confidence range is as big as the changes in this parameter.

A further important implication of climate warming in urban areas is the increased demand of electricity for cooling during the warm season. This increased demand may cause disruptions and overloading in the electricity network of the country, which may not be able to meet these high levels of demand. In Fig. 3d, the changes in the number of days per year requiring heavy cooling (i.e. days requiring cooling of more than 5°C from the base temperature of 25°C) per year are displayed. It is evident that more days per year will require heavy cooling, which leads to an increased use of air conditioning. Approximately 15 extra days per year will require cooling in Thessaloniki and Larissa and 10 extra days in Athens, Lamia, Kavala, Volos, Patras, Iraklio and Kalamata. The city with the smallest increases is Ioannina with only 5 extra days requiring heavy cooling per year. The signal of these changes is robust since the confidence range ranges from ±1 to ±5 days.

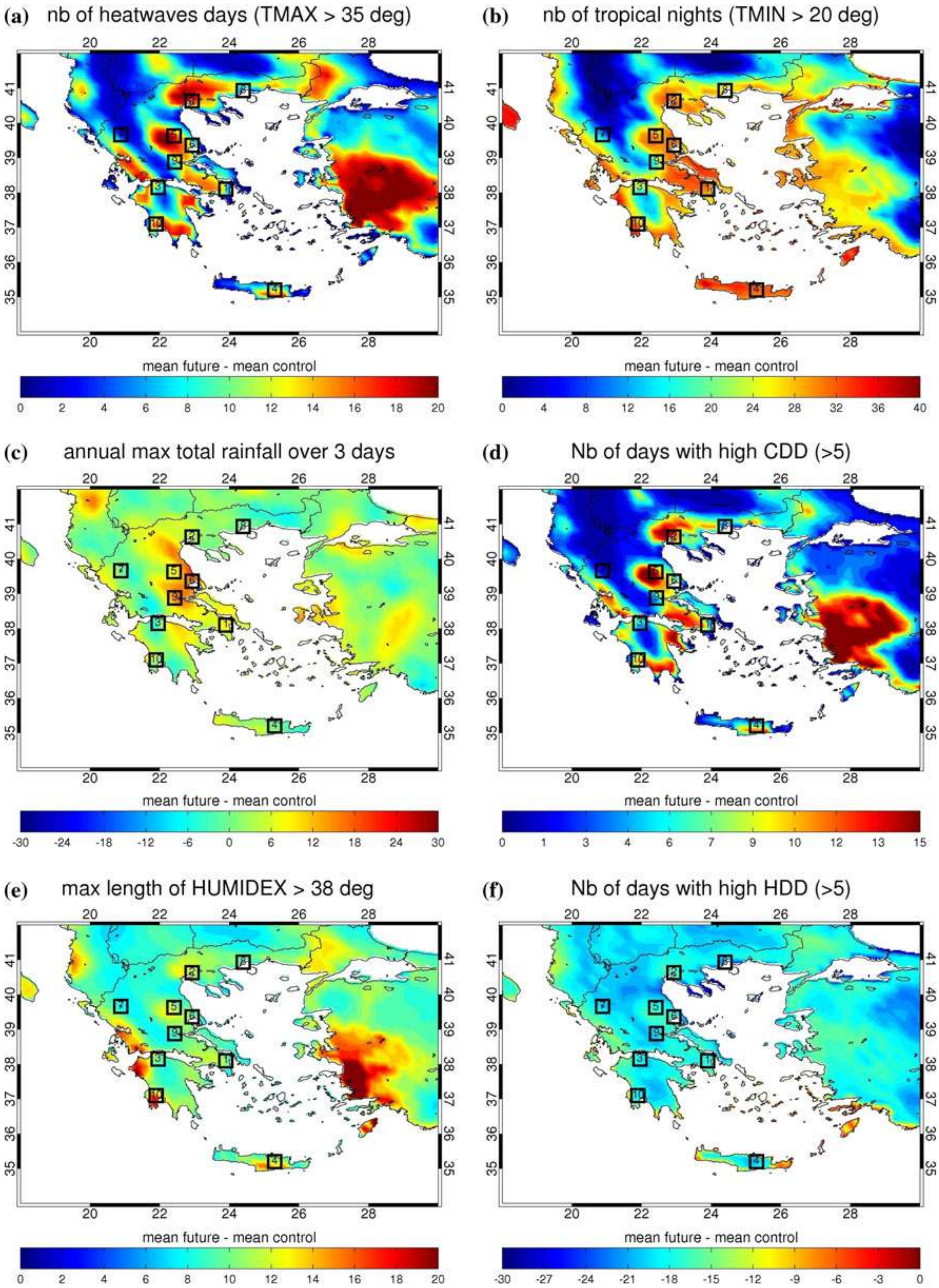

Fig. 3 Changes in **a** the number of heatwave days, **b** the number of tropical nights, **c** the maximum 3 day precipitation (%), **d** the number of days with high cooling demands, **e** the maximum length of days with humidex above 38°C, **f** the number of days with high heating demands between 2021–2050 and 1961–1990 for the selected urban areas of Greece

The above-mentioned results can be reinforced by the use of the humidex index expressing the apparent temperature and hence can be a proxy parameter of the need of an individual for cooling. Figure 3e displays the changes in the maximum length of days where humidex is above 38°C. It becomes evident that the maximum length of discomfort days increases everywhere, and coastal and island cities are no exception. For all cities, increases range from 10 to 13 days with the exception of Kalamata which will face the highest increase of about 16 extra days. Uncertainty is small since the confidence range is of much smaller than the changes.

Finally, a positive aspect of climate change in the urban regions is the reduced energy demand for heating during the cold period of the year. In Fig. 3f, changes in the number of days requiring heavy heating (i.e. days requiring heating of more than 5°C from the base temperature of 15°C) are presented. It becomes apparent from this figure that practically all urban areas in Greece will experience a decline of the heating requirements in winter season. More specifically, 15 (±8) fewer days requiring heavy heating per year are expected. The overall findings of the analysis regarding potential changes in urban areas in Greece are summarized in Table 4.

Tourist areas

Tourism represents one of the fastest growing global economic sectors. The tourism industry is clearly sensitive to climate and climate fluctuations in terms of the seasonal contrast between home and destination countries of tourists in Europe (Viner 2006). Studies indicate that climate conditions for tourism in northern and western Europe (Hanson et al. 2006), as well as in higher latitudes and altitudes (Scott et al. 2004; Amelung et al. 2007) might improve. Climate changes are therefore very likely to lead to a gradual shift of tourist destinations further north and up the mountains, affecting the preferences of sun and beach lovers from western and northern Europe for the Mediterranean (IPCC 2007b). Mountainous parts could become more popular because of their relative coolness. Higher summer temperatures may lead to a gradual decrease in summer tourism in the Mediterranean but an increase in spring and perhaps autumn. Scientific research has shown that Greece and Spain will experience a lengthening and a flattening of their tourism season by 2030 (Maddison 2001).

Climate is a principal component considered by tourists regarding travel planning, but its influence on local environmental conditions (e.g. water-shortages, wildfires, vector-borne diseases) may also deter potential tourists. For instance, following the devastating fires of summer 2000 in Greece (the amount of burnt area in 2000 is nearly three times the average amount for the total period of 1980–1999; EU 2001) more than 50% of all bookings from tourists for 2001 were cancelled (IUCN and WWF 2007). In addition, the exceptionally high temperatures during the 2003 heatwave in Western Europe led to an estimated 10% decrease in guest nights in the Spanish beach destination of Costa Brava during the summer season, while visits to inland mountain destinations increased as travellers sought comfortable climatic conditions (WMO 2005).

Occupancy rates associated with a longer tourism season in the Mediterranean will spread demand evenly and thus alleviate the pressure on summer water supply and energy demand. Water availability and supply may be heavily impacted as well as energy supply and demand. Specifically with increased energy demand to meet air conditioning needs, alternative ways for energy supply and generation must be sought. An indicative analysis of climatic parameters with direct or indirect implications for tourist areas has been undertaken for the most important

Table 4 Potential future changes in climate indices with particular relevance to urban areas

	No of heatwave days	No of tropical nights	Max 3 day rainfall (%)	High cooling demand (days)	Spell with humidex above 38°C (days)	High heating demand (days)
Athens	(+)15	(+)30	(+)10	(+)10	(+)10	(−)15
Thessaloniki	(+)20	(+)30	(+)10	(+)15	(+)12	(−)15
Patras	(+)20	(+)30	–	(+)10	(+)10	(−)15
Iraklio	(+)10	(+)30	–	(+)10	(+)13	(−)15
Larissa	(+)20	(+)30	(+)15	(+)15	(+)12	(−)15
Volos	(+)15	(+)30	(+)15	(+)10	(+)10	(−)15
Ioannina	(+)15	(+)15	–	(+)5	(+)10	(−)15
Kavala	(+)15	(+)30	–	(+)10	(+)10	(−)15
Lamia	(+)20	(+)30	(+)20	(+)10	(+)10	(−)15
Kalamata	(+)20	(+)30	–	(+)10	(+)16	(−)15

The (+) indicates increases, while (−) indicates decreases tourist destinations in Greece. These areas together with the number of available beds appear in Table 1.

In Fig. 4a, the changes in the number of days where temperature is above 35°C are shown, along with ten numbered squares which indicate the locations of the ten most popular tourist Greek resorts. Such high temperatures are expected to have an impact in population discomfort in the tourist areas. It is evident that tourist sites with a more continental or urban influence will experience the largest changes. For instance, Attica and Iraklio show a 15-day increase. The other tourist sites in Crete, namely Chania and Rethymno, show smaller increases of approximately 10 days. Similar are the findings for Pieria, Chalkidiki, Rhodes and Corfu. Smaller island sites with a more pronounced sea influence, present even smaller changes. Zante/Cephalonia show an increase of only 5 heatwave days, which is nevertheless important whether one considers the fact that such temperatures have not been recorded in the present day period at these sites. Cyclades islands are shown to retain much of their coolness with negligible increases in the hot days. Confidence ranges are about ±2 days.

In the previous section, it was discussed that 'tropical nights' are closely associated with population health and discomfort. Figure 4b illustrates changes in this parameter for the selected tourist sites in Greece. It becomes clear that tropical nights increase almost everywhere and in this case island sites are affected even more than continental areas. It is estimated that all selected tourist sites will experience about an extra month (±7 days) of warm nights per year.

To assess public comfort, changes in the number of days with apparent temperature (humidex index) above 38°C are also examined. Figure 4c presents changes in this parameter for the touristic areas of Greece. Changes imply that the feeling of discomfort will increase in all areas. More specifically, the highest changes of about 30 (±6) days are evident in Rhodes and Iraklio whereas the lowest changes of about 7 (±2) days are evident in Cyclades. The change in this parameter means that high temperatures coupled with increased humidity levels close to the sea will further add to the discomfort of tourists.

Changes in the number of summer days per year have also been examined. A summer day is defined as a day with maximum temperature (*T*max) above 25°C. Increases in this parameter might lead to a lengthening of the tourism season and consequently a relief of the pressure in the peak summer months of July and August. Figure 4d presents the changes in maximum length of summer days for the selected tourist areas in Greece. More than 20 (±7) additional summer days are expected in all tourist areas of Greece. This estimation may increase to 30 (±7) (i.e. an extra month per year) in coastal areas of Crete (Chania and Rethymno). This practically indicates extension of the tourism season by as much as 1 month per year in these areas.

Another important implication of climate warming in tourist areas is the increased demand of energy for air conditioning in summer. In Fig. 4e, the changes in the number of days per year requiring heavy cooling per year are plotted. In particular, most areas will require more than 5 (±2) additional days with heavy cooling, implying an increased use of air conditioning. The Cyclades islands and Zante/Cephalonia are two areas that do not present future changes in the number of days requiring heavy cooling.

Finally, Fig. 4f shows changes in extreme forest fire risk occurrence, a parameter of great importance for tourist areas since an increased number of forest fires may drive tourists away and also a burnt landscape acts as a deterring factor for tourism. It becomes evident that extreme forest fire risk increases by around 10 days in Rhodes, Corfu, Iraklio, Chania, Rethymno. Attica, Chalkidiki and Pieria exhibit a 15-day increase whereas the Cyclades islands and Zante/Cephalonia show negligible changes. Confidence limits are about ±3 days. The overall findings of the analysis regarding potential changes in tourist areas in Greece are summarized in Table 5.

Conclusions

The present study presents future projections of potential climate change impacts. In the near future, namely the period 2021–2050, climate conditions are expected to deteriorate compared with the reference period (1961–1990) conditions The main finding of this study are summarized below.

Regarding agriculture, the length of the longest dry spell is expected to increase in most of the studied regions. In Evia and other sub-regions in the northern part of the country, at least 20 additional dry days are projected to occur every year in the period 2021–2050. The changes in the number of days with fire risk are also an important parameter for agricultural areas with trees (such as olive, orange, peach trees). Fire risk days increase substantially everywhere. The most considerable increases are estimated in the agricultural regions of central Greece with up to 20 more days of fire risk per year. As far as precipitation is considered, winter precipitation generally decreases with more substantial decreases of 15% occurring in the areas of Serres, Pella and Iraklion. In contrast, an increase in autumn precipitation is projected in most agricultural areas. In particular, the areas of Larissa and southern Evia will experience increases of up to 20%, whereas Pella and Iraklion will see increases of around 15%.

Devastating forest fires in Greece occurred in summer 2007, with the loss of human lives, destruction of many villages and hundreds of square kilometres of forest burned. Changing climate conditions related to increased

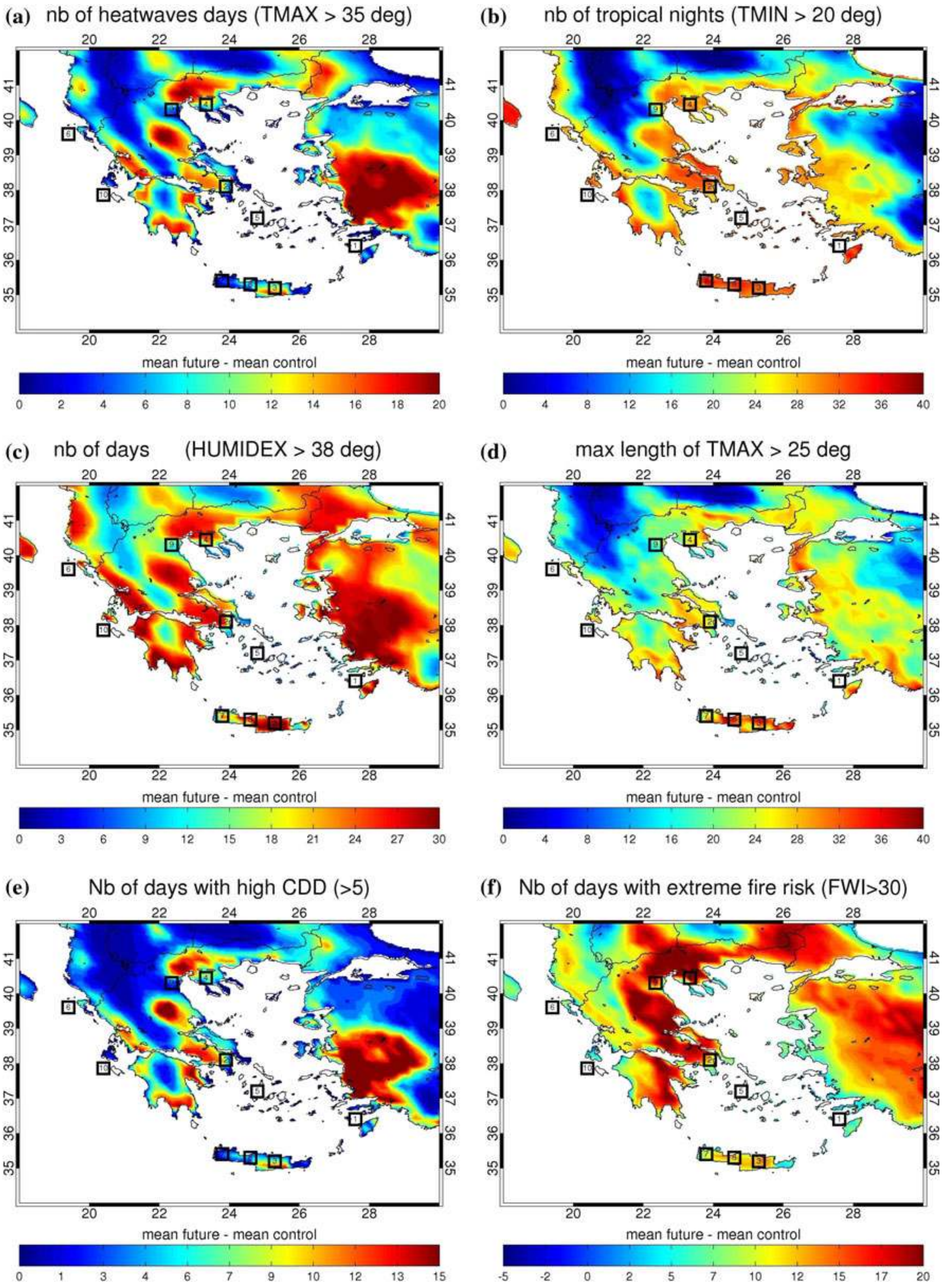

Fig. 4 Changes in **a** the number of heatwave days, **b** the number of tropical nights, **c** the number of days with humidex above 38°C, **d** the maximum length of spell with *T*max > 25°C, **e** the number of days with high cooling demands, **f** the number of days with extreme fire risk (FWI > 30) between 2021–2050 and 1961–1990 for the selected tourist areas of Greece

Table 5 Potential future changes in climate indices with particular relevance to tourist areas

	No of heatwave days	No of tropical nights	Humidex above 38°C (days)	Max length of summer days	Heavy cooling demand (days)	Forest fire risk (days)
Rhodes	10	35	30	25	5	10
Attica	15	30	25	25	10	15
Iraklio	15	30	30	25	10	10
Chalkidiki	10	30	20	25	5	15
Cyclades	–	30	7	25	–	5
Corfu	10	30	25	20	5	10
Chania	10	30	20	30	5	10
Rethymno	10	30	25	30	5	10
Pieria	10	30	17	20	5	15
Zante/Cephalonia	5	30	25	25	–	5

All changes indicate increases in the examined climate indices

minimum temperatures (approximately 1.3°C) and decreased winter precipitation by 15% on average suggest that the risk for forest fires gets intensified in the future. It is estimated that the number of days with extreme fire risk will increase by 10–15 days per year.

Climate change is expected to result in warmer temperatures in urban areas, which translate into more days with maximum temperature above 35°C and night temperatures exceeding the 20°C. In some cases, flash floods events are expected to become more frequent. Unpleasantly, high temperatures and relative humidity combined with the lack of green spaces will increase the feeling of discomfort in the citizens of big cities. For instance, Thessaloniki, Patras, Lamia and Larissa are expected to experience up to 20 more hot days, and almost an additional month with night-time temperatures higher than 20°C. The total annual precipitation is found to decrease in Lamia, Larissa, Volos, Thessaloniki and Athens. However, the amount of a 3-day precipitation event seems to increase by 10–20%. Hence, extreme rainfall episodes tend to occur more frequently. Another impact of climate change in urban regions is the increase in energy demand for cooling in summer and the decrease in demand for heating in winter. However, the winter and summer loads do not counterbalance each other, as the energy consumption required for cooling in summer is greatest at specific days and times of the day.

The tourism industry is a vital economic sector and occupies a dominant position in the Greek economy. Fully understanding its importance, this study has investigated potential impacts in tourist areas due to climate change. It was found that continental tourist areas of the Greek mainland will more often face heatwave episodes. In most of the studied regions, 5–15 more days exceeding the 35°C threshold will occur every year. The largest increases are found in 'summer' days (>25°C) and 'tropical' nights (>20°C). The former can be considered as a positive impact as it may prolong the tourist period. The number of 'tropical' nights per year seems to substantially increase especially in the islands. For example, Rhodos and Chania expect a sum of 40 additional 'tropical' nights. In coastal regions, such warm conditions in combination with high levels of relative humidity can result in uncomfortable conditions for foreigners and the local people.

It is important to underline that the evidence emerging from this work is subject to some degree of uncertainty since the analysis is based on climate scenario data. We have attempted to estimate uncertainty in our projections for each parameter examined and our results are encouraging for all indices associated with temperature. However, indices associated with precipitation, such as droughts, extreme precipitation or even fire risk, are subject to higher levels of uncertainty, stemming from the episodic nature of precipitation and its high regional variability. Therefore, indices linked to precipitation should be viewed with caution. However, it is important to communicate such evidence among the scientific community and the policy makers in order to plan adaptation strategies to minimize the impacts of climate change at a regional level.

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