Climate Change and Morphological Stability

Greece scale

Co-Evolve4BG

Analysis of Threats and Enabling Factors for Sustainable Tourism at Pilot Scale

Climate Change and Morphological Stability

Greece Scale

REGION OF EASTERN MACEDONIA & THRACE

OVERVIEW

The present document was produced in the framework of **Co-Evolve4BG project “***Co-evolution of coastal human activities & Med natural systems for sustainable tourism & Blue Growth in the Mediterranean” in relation to Threats and Enabling Factors for maritime and coastal tourism development on a national scale” Co-funded by* ENI CBC Med Program (Grant Agreement A_B.4.4_0075).

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Abstract

This deliverable aims to identify the challenges and threats regarding the morphological stability of Greek coastal areas, which developed through the review of existing data at a national and regional scale.

The document structures contain:

Section 1 - Provides an overview of present and possible future trends of Climate, Sea Temperature, and Sea Level at Greece level with consideration to Climate Change.

Section 2 - Highlights the morphological characteristics of Greece's coastal zones.

Section 3 - Focuses on reporting the evolution of Greece's coastal zones considering the foreseen relative Sea Level Rise scenarios and the present erosion trend.

I. Introduction

Climate change is considered a phenomenon that will cause long-term changes in the global average physical weather patterns. Most of the scientific community recognizes climate change as one of the fundamental environmental problems facing all countries worldwide.

Observed changes in Earth's climate from the 20th century mainly stem from human activities, particularly by fossil fuel burning, which causes an increasing heat-trapping greenhouse gas levels in Earth's atmosphere, resulting in an increase in the average temperature at the Earth's surface.

The effects of climate change could be catastrophic, mainly for vulnerable marine and coastal areas, even affecting the structure and activity of their ecosystems. The upward trend in sea level (1.7 mm/year) around the globe is rapidly modifying the shape of the coasts in general. It negatively contributes to the devastating phenomenon of coastal erosion, which leads to other secondary events such as flooding and underground saltwater intrusion. This continuing situation will undoubtedly lead to severe and irreversible impacts on the morphology of the coastline, the preservation of natural resources, the sustainability of the marine and coastal environments, and the stability of socio-economic activities in the coastal zone maintenance of the infrastructure where these activities take place (NASA portal1)

The Mediterranean Sea surrounds Greece, a country characterized with a Mediterranean climate. The climate characteristics vary from place to place, with mild and wet winters in the lower southern part of the country and island areas; on the other hand, the mountainous regions, with cold winters and intense snowfalls; and in central and northern regions with hot dry summers. Greece has one of the longest coastlines in the world, with 16,300 km, of which approximately 1,000 km are areas characterized as highly vulnerable to climate change. (World Bank2, 2020)

In Greece, the impacts of global warming have already become apparent. Numerous adverse effects on the coastal ecosystem and natural resources are already beginning to influence the Greek coasts with the instability observed at the level of coastal morphological forms, the flooding of lowland near the coastal areas, the appearance of several exotic species in the marine environment at the expense of endemic aquatic species.

These deliverable searches and provides an overview of the impacts of climate change on key atmospheric and oceanographic variables and implications for coastal morphology in Greece.

1 https://climate.nasa.gov/resources/global-warming-vs-climate-change/

2 https://climateknowledgeportal.worldbank.org/country/greece

II. Climate Changes Characteristics

II.1. Introduction

Sea level has been constantly changing since geological time due to many different natural processes. An integrating approach had to be distinguished from a strategy that will separate land-level changes from sea-level changes. It is another form of sea level difference due to different shapes of ocean basins from changes caused because by the break-up of continental masses (Emery and Aubrey, 1991). However, to respond effectively to current climate challenges, it is crucial to focus on contemporary influencing factors related to sea level change and not those that have played a critical role in the past.

Nowadays, several factors impact sea level and have different spatiotemporal scales (Cazenave and Llovel, 2010), which means that their effects could be short or long term. Short-term factors are, for instance, the seasonal and diurnal variations in atmospheric pressure: winds and storm surge, astronomical tides, tsunamis, or the El Niño–Southern Oscillation (ENSO). These phenomena can range from a few seconds to years. On the other hand, long-term factors are more difficult to observe or record because they have a fuller time range. These factors could be the changes in the size of ocean basins (due to variations in the lithosphere), in the mass of ocean water bodies (determined chiefly by the melting or accumulation of continental ice), or the thermal expansion of water (due to the warming of ocean surface waters).

II.2. Global Scale Projections

United Nations' responsible organization for assessing all the scientific issues related to climate change is the Intergovernmental Panel on Climate Change (IPCC, 2013). IPCC produced highly scientific assessment reports related to climate change, which play a crucial role in international negotiations to confront climate change. The IPCC was established by the U.N. Environment Program in cooperation with the World Meteorological Organization (WMO) in 1988 and had 195 Member countries[3].

The IPCC Expert Panel is working on a global-scale modeling based on four Representative Concentration Pathway (RCPs) used to produce the IPCC's 5th Assessment Report, in which it made several predictions regarding the impacts of climate change. The four pathways were used to construct different climate models and research for the IPCC's 5th Assessment Report (AR5) in 20144. The four pathways used to describe that different climate scenarios can occur and depend on the number of greenhouse gases (GHGs) emitted into the atmosphere over the next few years. The four possible scenarios of increasing surface air temperature, based on selected assumptions, include levels of population growth, economic and commercial activities, and levels of energy consumption.

3 https://www.ipcc.ch/
4 https://en.wikipedia.org/wiki/Representative_Concentration_Pathway

II.2.1. Global Surface Temperature

A question that the scientific community needs to answer as a matter of priority is "How is the temperature on Earth changing?"

Since the last century, it has become possible for humans to make instrumental atmospheric observations. These observations have shown that the planet's surface temperatures exhibit a global supervenience, with wide regional variations. Warming in the last century on a worldwide average has occurred in two distinguished phases, the first one was from the 1910s to the 1940s (0.35 °C); and the second one, more severe, was recorded from the 1970s to the present day (0.55 °C). Over the past 25 years, 11 of the 12 warmest years on record and a generally increasing rate of warming has been observed. in addition, up to 10 km above the Earth's surface in the troposphere since the 1950s, the atmosphere has warmed to a degree slightly greater than that at the surface. The stratosphere (about 10 to 30 km) has cooled, especially since 1979. The variety in the temperatures was not a surprise since it was according to physical expectations and models' results. Oceans' warming, sea level rising, glaciers melting, and sea ice retreating in the Arctic simultaneously diminished snow cover in the Northern Hemisphere confirm the change of the climate and the warming temperatures.

At a global level, average surface temperatures have risen at 0.74 °C ± 0.18 °C, after an estimation using a linear trend on the last 100 years (1906–2005). over the past 50 years, the rate of warming has nearly doubled compared to 100 years ago (0.13 °C ± 0.03 °C versus 0.07 °C ± 0.02 °C per decade).

At a global level, the estimated evolution of the surface temperature which until the end of the 21st century is very likely to exceed 1.5° C compared to 1850 to 1900 for the three RCP scenarios, with different results for the RCP 2.6 (1st scenario). Especially regarding the three scenarios, it is likely to exceed 2 °C for RCP 6.0 (3rd scenario) and RCP 8.5 (4th scenario – worst-case scenario) and 2 °C lower for RCP 4.5 (2nd scenario). The results of the model projection RCP scenarios (except RCP 2.6) show that the warming will continue beyond 2100. Studies show that the warming will continue to persist until recently in interannual-to-decadal variability and will continue to be characterized by regional variation.

From the period 2016 to 2035, it should be noted that the range of change in global mean of surface temperature is related to the 1986–2005 ranges, which means that it should remain between 0.3 °C to 0.7 °C (medium confidence). This assessment takes as the fact that there will be no significant volcanic eruptions or material changes in total solar irradiance and works on multiple lines of evidence to achieve a realistic prediction. In addition, the natural internal variability, expected to be higher in the tropics and subtropics than in mid-latitudes (high confidence), taking into consideration the short-term increases in seasonal and annual average temperatures (Hegerl *et al.* 2007) underestimating substantial delays in the climates response to anthropogenic forcing. We report experiments with highly educated adults graduate students at MIT showing widespread misunderstanding of the fundamental stock and flow relationships, including mass balance principles, that lead to long response delays. GHG emissions are now about twice the rate of GHG removal from the atmosphere. GHG concentrations will therefore continue to rise even if emissions fall, stabilizing only when emissions equal removal. In contrast, most subjects believe atmospheric GHG concentrations can be stabilized while emissions into the atmosphere continuously exceed the removal of GHGs from it. These beliefs analogous to arguing a bathtub filled faster than it drains will never overflow support wait-and-see policies but violate conservation of matter. Low public support for mitigation policies may arise from misconceptions of climate dynamics rather than high discount rates or uncertainty about the impact of climate change. Implications for education and communication between scientists and nonscientists (the public and policymakers.

CMIP5 (Coupled Model Intercomparison Project Phase 5) model simulations' results for the period 2081-2100 show an increasing average surface temperature globally, in relation to 1986–2005. RCP measurements show that for scenario RCP 2.6 is between 0.3 °C and 1.7 °C, for scenario RCP 4.5 is between 1.1 °C and 2.6 °C, for scenario RCP 6.0 is between 1.4 °C and 3.1 °C, and for scenario RCP 8.5 is between 2.6 °C to 4.8 °C. Furthermore, the model's results show that the Arctic Region warming will follow at a higher rate than the global one. The mean warming over lands will also be higher than the oceans (very high confidence).

Compared with the average global surface temperature for the years between 1850 and 1900, model results show that until the end of the 21st-century, the changes probably exceed the 1.5 °C for the scenarios RCP 4.5, RCP 6.0, and RCP 8.5 (high confidence). Regarding the warming, because of climate change, it is likely to exceed 2 °C for the scenarios RCP 6.0 and RCP 8.5 (high confidence), not to exceed 2 °C for the scenario RCP 4.5 (high confidence), and it isn't very sure to exceed 2 °C for the scenario RCP 2.6 (medium confidence). In addition, warming is unlikely to exceed 4 °C for the scenarios RCP 2.6, RCP 4.5, and RCP 6.0 (high confidence), and it is questionable if it will exceed the 4 °C for the worst-case scenario RCP 8.5 (medium confidence).

It is estimated that the increase in global average temperatures will lead to more frequent extreme hot and lower cold temperatures, mainly over land on a daily and seasonal scale. The heat waves will occur with an increasing frequency and period, and rare cold winter extremes will continue to happen.

Figure 1 presents the results from the IPCC AR5 report followed by the experiments with the CMIP 5. CMIP 5 is the last edition and most extensive and updated CMIP. Test suites separated into three classes define it:

1. Retrospective decadal simulations and forecasts.
2. Long-term simulations.
3. Atmospheric-only simulations (prescribed sea surface temperature -SST) for incredibly computationally demanding models.

CMIP is a common and standard experimental framework that allows studying coupled circulation models for the atmosphere and the ocean. This experiment suite facilitates various assessments regarding strengths and weaknesses under different climate models and enables enhancement and focus in developing future models in specific periods. For instance, if the models present a wide range of different values either at a regional or a global level, scientists can determine the cause(s) of this uncertainty [5].

CMIP5 multi-model simulated time sequence from the period of 1950 to 2100 (Fig. 1) for the 3 measurements below:

1. The change in global averages of annual surface temperature for the period between 1986 and 2005.
2. The Northern Hemisphere September Sea ice extent in a 5-year running mean.
3. The global average ocean surface recorded Ph8.1.

The time sequences of projections and uncertainty measures (shaded) are shown in blue for RCP2.6 scenarios and in red for RCP 8.5. The black color (grey shading) is the modeled historical trend using reconstructed historical data. The mean and associated uncertainties averaged from 2081 to 2100 are given for all RCP scenarios as colored vertical bars. The numbers of the CMIP5 models used to calculate the multi-model means are presented. For the sea ice extent (graph b), the projected mean and uncertainty of minimum and maximum range of the subset of models most closely represents the average climatological situation from 1979 to 2012 trend for the given Arctic Sea ice. Additionally, the CMIP 5 multi-model mean is also indicated by dashed lines. The dashed line represents nearly ice-free conditions. (IPCC, 2013).

5 https://climatedataguide.ucar.edu/climate-model-evaluation/cmip-climate-model-intercomparison-project-overview

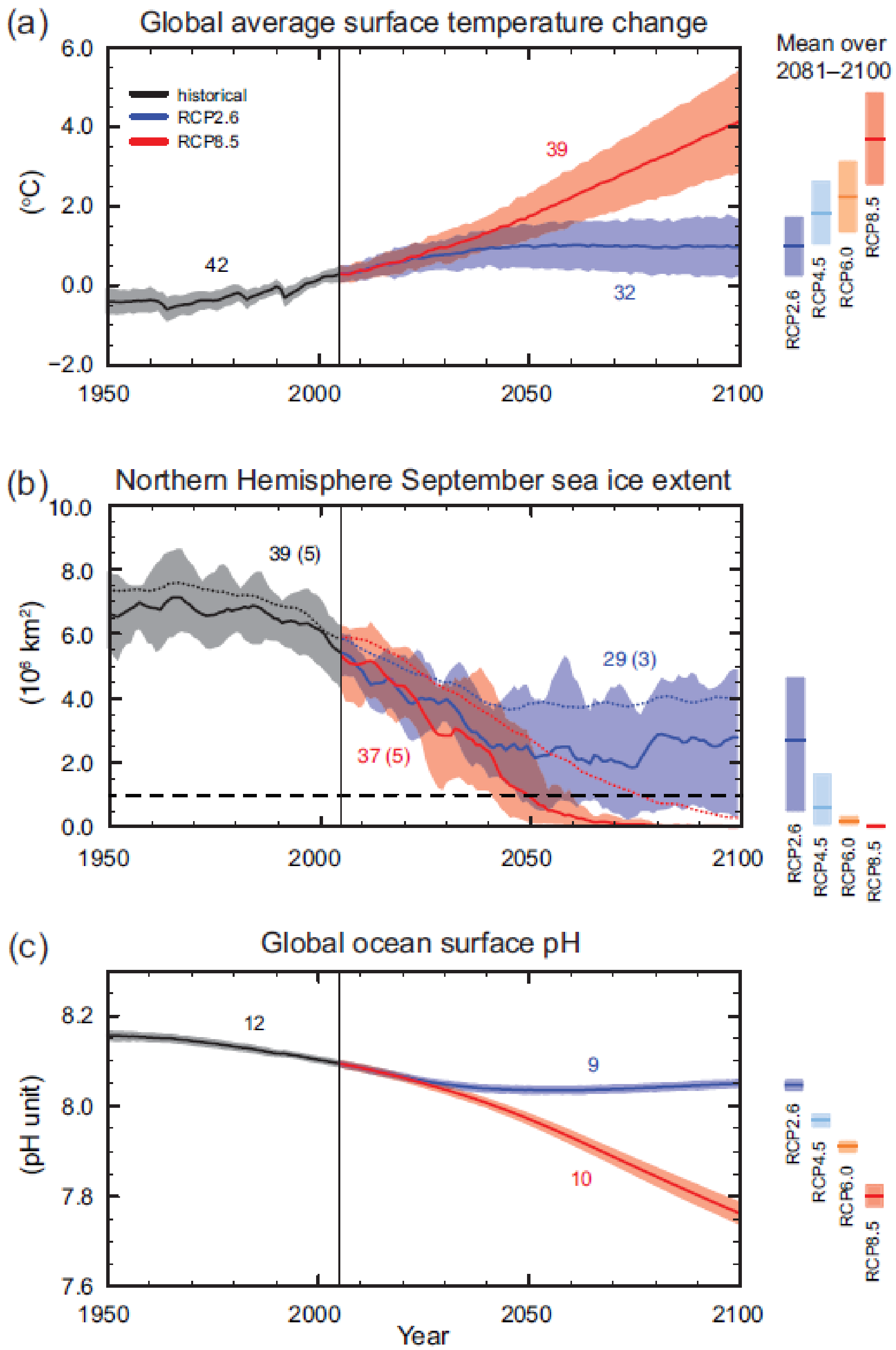


Figure 1. CMIP5 multi-model simulated time series for the period from 1950 to 2100 (IPCC, 2013)

II.2.2. Global Mean Sea Level - GMSL

Historically, the highest recorded value of global mean sea level (GMSL) reached just in 2019 and in the last 100 years has risen approximately 19 cm, at a rapidly increasing rate. Global warming is considered as one of the significant factors, which influence the GMSL.

The IPCC AR5 after the experiments and projections with the CMIP5 found that GMSL rise (Fig. 2) for 2081 to 2100 (in reference to 1986 to 2005) will likely be for scenario RCP2.6 in the range between 0.26 to 0.55 m, scenario RCP 4.5 from 0.32 to 0.63 m, scenario RCP6.0 from 0.33 to 0.63 m and for the scenario RCP 8.5 from 0.45 to 0.82 m (medium confidence). For the scenario RCP 8.5 (worst case scenario), the rise of the year 2100 is estimated to be 0.52 to 0.98 m, with a predicted rate of 8 to 16 mm yearly, from 2081 to 2100 (medium confidence). Considering that there is a great possibility of faster disintegration of the polar ice sheets, the projections data show a possible rise of up to 2.4 m in 2100 and 15 m to 2300. Another reported fact is that most of the coastal regions of Europe have experienced a trend of sea level rise around land level, except for the northern Baltic coast, where different trends follow.[6]

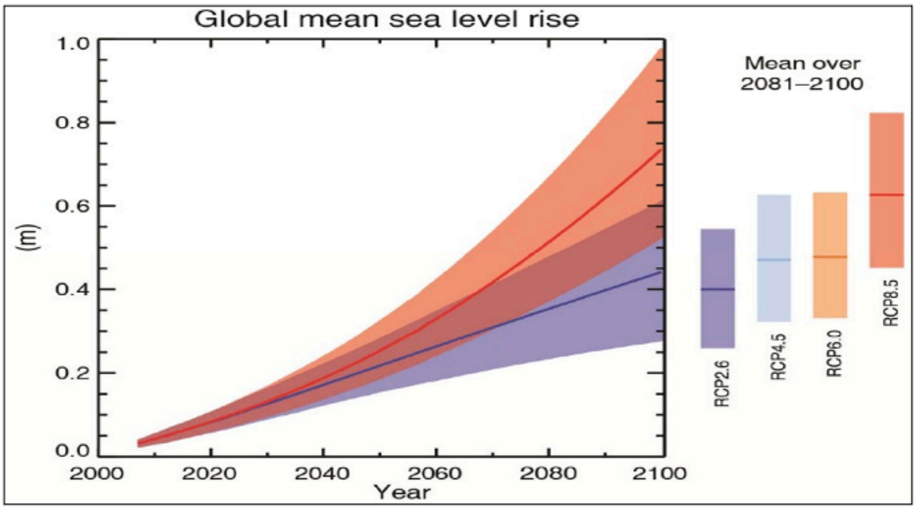


Figure 2. Sea Level Projection between 2000 and 2100 (IPCC, 2013)

II.3. Climate in Greece

Greece is in the most south-eastern part of the European continent, linked to the geographical areas between the 34 and 42 parallels North, with a southern extension from 19 to 28 East and surrounded by the Aegean, Ionian, and Eastern Mediterranean Seas. The climate in Greece is characterized by the hot and dry summers and relatively cold and wet winters as general as the Mediterranean climate (Fig. 3). Significantly, the northern part of Greece is frequently freezing during the winter and snow is not unusual. On the other hand, in the south of Greece and the islands, the winters are milder. During the winter, a lot of snowfall can be expected at high altitudes and in the mountains.

6 https://www.eea.europa.eu/data-and-maps/indicators/sea level-rise-7/assessment

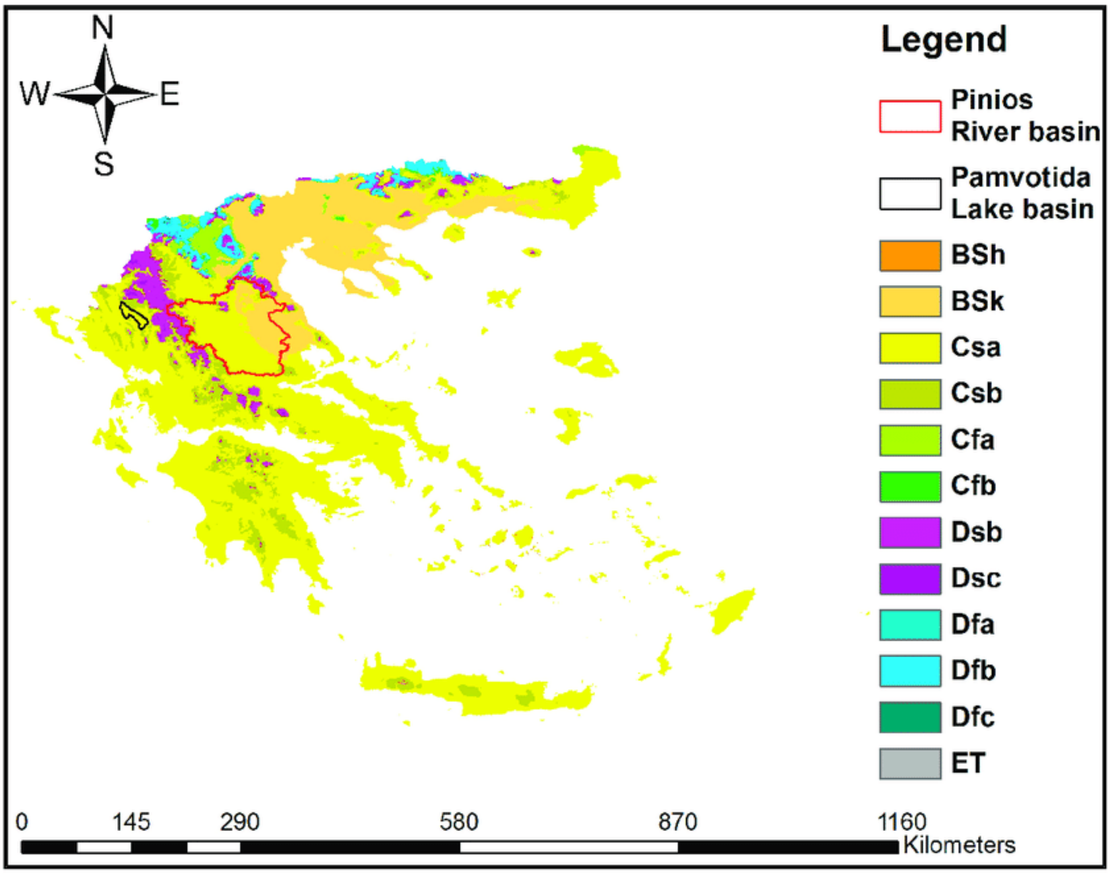


Figure 3. Greece's Köppen climate types' map (Papaioannou *et al.* 2021)

II.3.1. Atmospheric Temperature

Many studies examined the temperature trends in Greece. The statistical records show high negative trends from 1960 to 1976 and positive ones from 1977 to 2004. Other researchers show that in the period between 1960 and 1976, the lowest recorded minimum annual temperature was observed in Crete in the southern part of Greece. From 1977 to 2004, crucial yearly warming was recorded in the northern region of Greece. Moreover, the lowest warming was observed in the central and north Aegean Sea and the semi-mountainous areas.

Greece is characterized by high seasonal fluctuations, with the highest observed in the northern and eastern regions and the Attica area. Another data is that the average annual temperature trends in the north of Greece follow the hemispheric trends[7] (Fig. 4).

7 (4) Recent trend analysis of mean air temperature in Greece based on homogenized data. Available from: https://www.researchgate.net/publication/281230089_Recent_trend_analysis_of_mean_air_temperature_in_Greece_based_on_homogenized_data [accessed Apr 18, 2021].

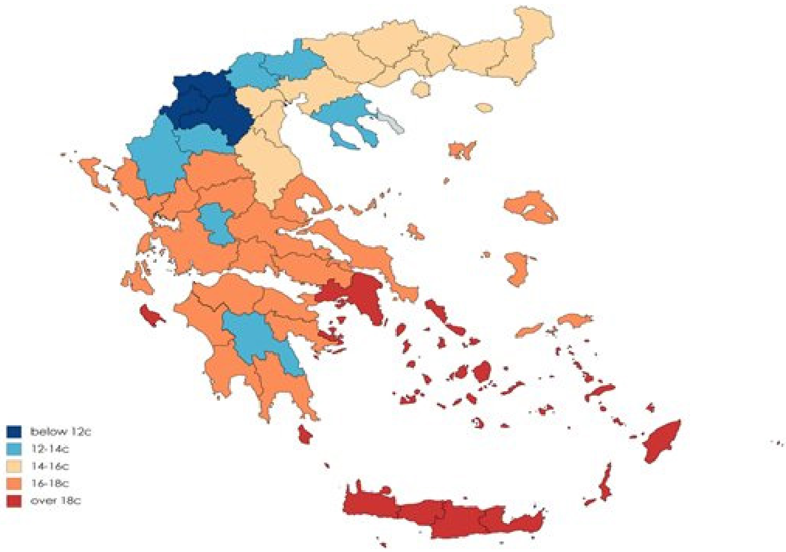


Figure 4. Average annual temperature in Greece (Bompolakis, 2019)

Research Centre for Atmospheric Physics and Climatology –(RCAPC), which belongs to the Academy of Athens, has developed model simulation datasets regarding climate change adopting four different scenarios related to the additional greenhouse gas emissions. The four Scenarios named with the alphanumeric names A2, A1B, B2, and B1 (Table 1) developed in the context and alongside the United Nations IPCC 3rd Assessment Report for the Climate Change (Nakicenovic *et al.* 2000).

Table 1. Greenhouse gas emission scenarios of the Climate Change Impacts Study Committee (CCISC) based on IPCC AR3 (Zerefos *et al.* 2011)

Scenario A2	Moderate increase in global average per capita income. Particularly strong energy consumption. Rapid rise in global population. Slow and fragmented technological change, and modest to major changes in land uses. **Rapid** rise in CO2 concentration in the atmosphere, to **850 ppm** by 2100.
Scenario A1B	Rapid economic growth. Particularly strong consumption of energy, but also spread of new and efficient technologies. Use of both fossil fuels and alternative energy sources. Small changes in land uses. Rapid rise in global population by 2050 and gradual decline thereafter. **Large** increase in CO_2 concentration in the atmosphere, to **720 ppm** by 2100.
Scenario B2	Development of global economy at modest rates. Smaller technological change compared to Scenarios A1 and B1. Rapid rise in global population. Increase in CO_2 concentration in the atmosphere **at modest but steady rates**, to **620 ppm** by 2100.
Scenario B1	Large increase in global per capita income. Low energy consumption. Reduced use of conventional energy sources and shift towards renewable energy. Rapid rise in global population by 2050 and gradual decrease thereafter. Increase in CO_2 concentration in the atmosphere at a relatively **mild pace**, particularly as of 2050, to **550 ppm** by 2100.

Greece's climate stimulation gave analytical results regarding the mean atmospheric temperature. Especially, running the model with scenario A1B (Fig. 5), reference period from 1961 to 1990, predicts the projected variation in annual average air temperature. The results are in Figure 5, for the period between 2021 to 2050 on the left map and 2071 to 2100 on the right one. Figure 5 shows that all regions of Greece are predicted to present 1.5°C higher annual mean temperatures for the period between 2021 and 2050. Based on the current climate trends, the temperature increase is more elevated in summer and lower in winter. During the next decade 2091 to 2100, it is estimated that the average temperature in Greece will be higher (than in the reference period) by 4.2 °C in summer, 3.2 °C in winter, and ~3.5 °C in spring and autumn (Zerefos *et al.* 2011).

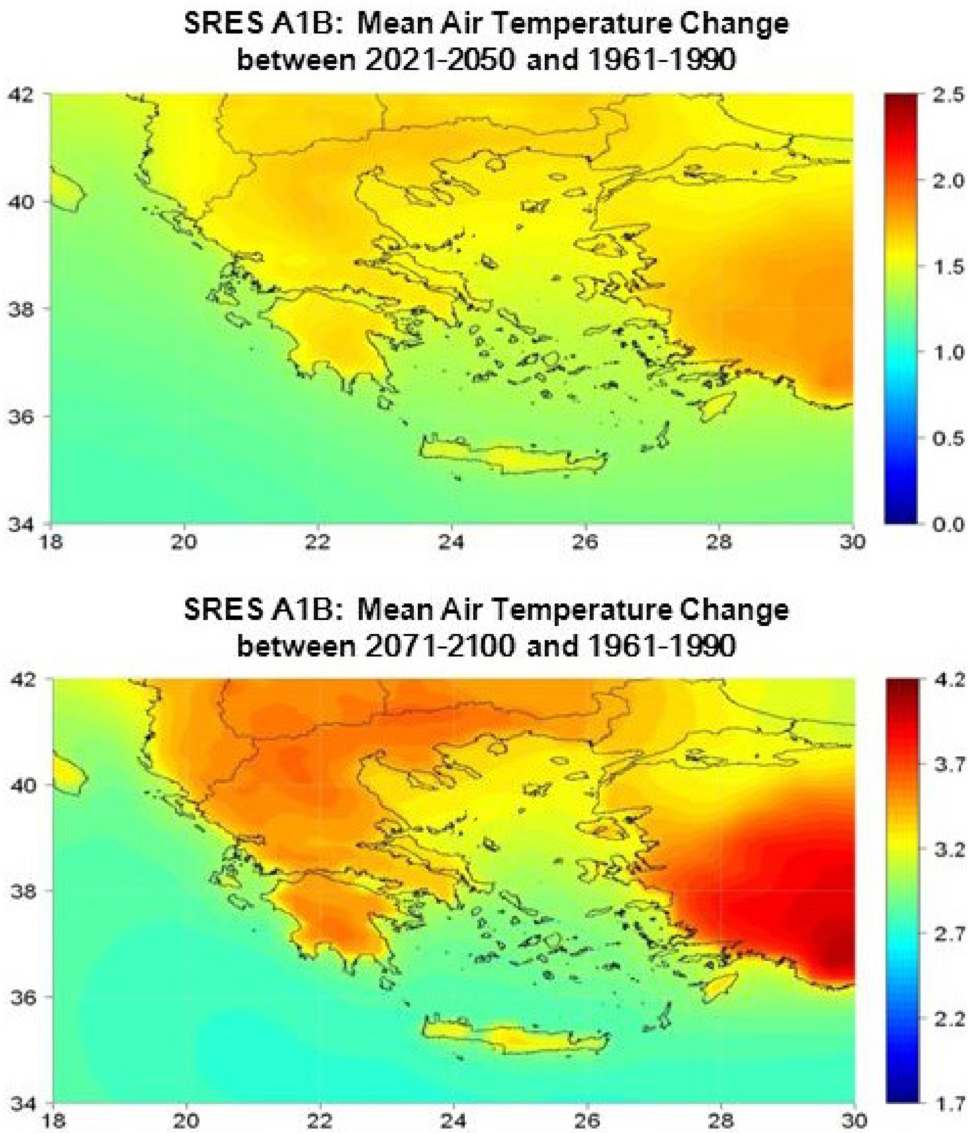


Figure 5. Variation in the mean air temperature in (a) 2021-2050 and (b) 2071-2100, in reference to 1961-1990 (Zerefos et al. 2011)

Differences in estimated atmospheric air temperature present significant variation by using the four emission scenarios. Climate simulations under all four-emission scenarios (Fig. 6) predict overall average warming in Greece over the coming decades compared to the reference period from 1961 to 1990. Scenario A2 shows the highest increase in temperature, and Scenario B1 the lowest. Warming is also projected to be higher in continental regions than in islands and lower in spring and winter and higher in fall and summer, each year.

Scenario A2 projection regarding the average air temperature in Greece shows to be 3.9 °C higher in winter and spring, 5.4 °C is higher in summer, 4.7 °C higher in autumn and 4.5 °C higher year-round, for the decade from 2091 to 2100. In addition, scenario B2 shows annual average warming at the end of the 21st century to be ~1.3 °C lower than Scenario A2. Finally, the B1 scenario shows that the projected warming shows lower temperatures than the other three scenarios. In particular, the mean air temperature in all regions of Greece for the period from 2091 to 2100 is estimated to be higher, based on the reference period, by 2° C in winter, 2.2 °C in spring, 3 °C in summer and 2.4 °C in autumn (Zerefos *et al.* 2011).

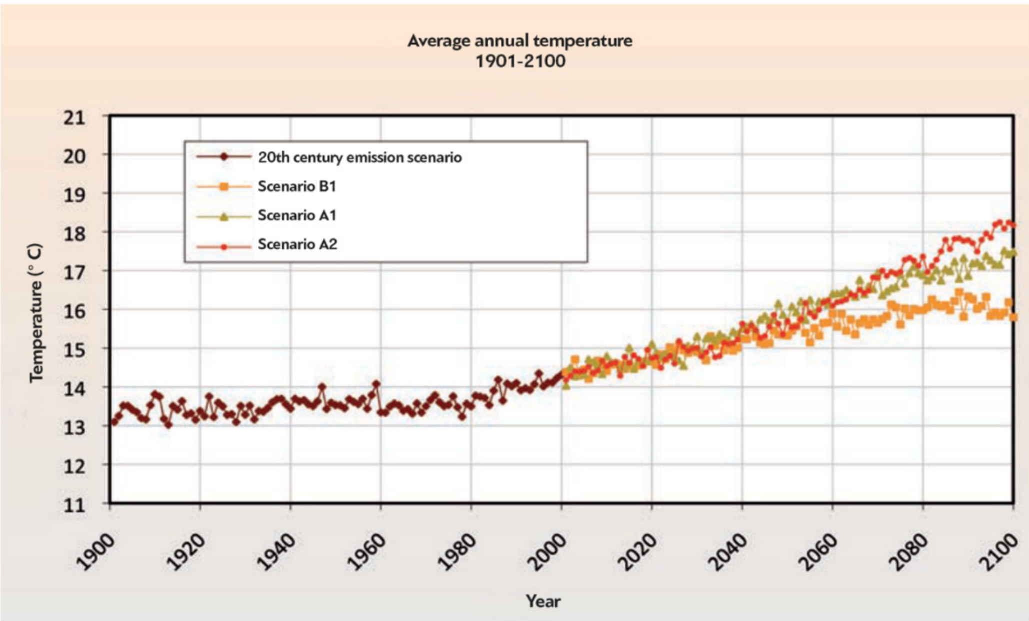


Figure 6. Variation in the average annual temperature in Greece during the period of 2000-2100 and under the Scenarios B1, A1B, and A2 (Zanis *et al.* 2009)

II.3.2. Climate Extremes

Between the end of the 19th century and the 1970s, the temporal sequence of mean atmospheric temperature for the eastern Mediterranean and Greece was constant with an upward trend identical to that recorded for the Northern Hemisphere – N.H. (Fig. 7; Zanis *et al.* 2009). In Greece, a high cooling period was recorded from 1940 to 1970 (Zerefos *et al.* 2011). Analytical records were used from weather stations in different cities (Fig. 8) and observed this cooling trend. After 1970, the mean average temperature in Greece shows a consecutive increase and the model projections show a continuous upward trend for the future.

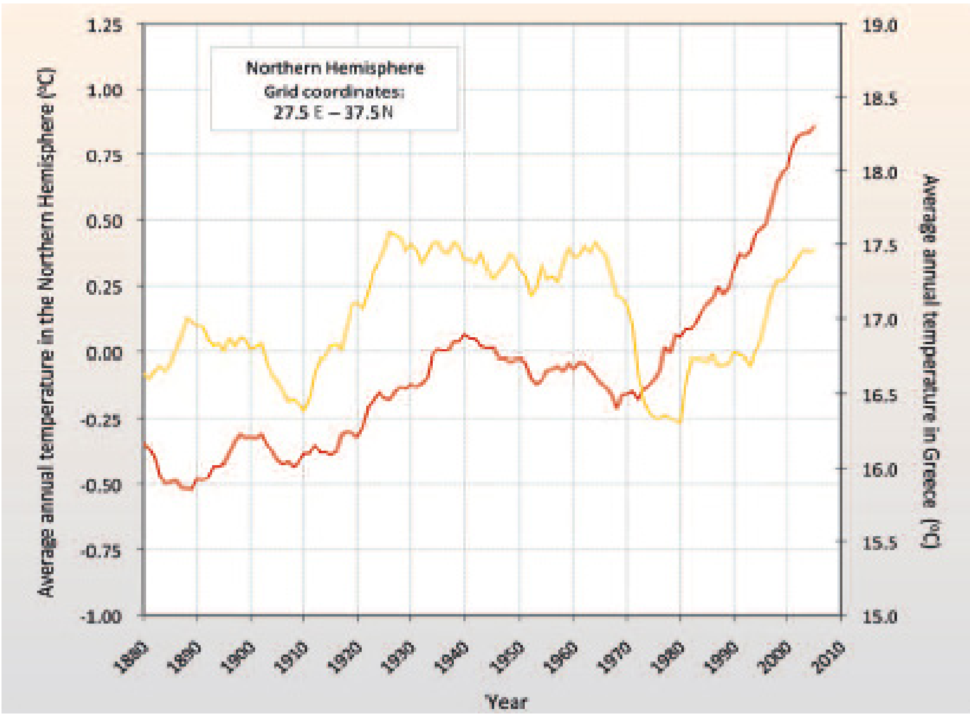


Figure 7. Mean annual temperature period, 1880-2010.The Red line represents the Northern Hemisphere. The Yellow line represents Greece. (Zanis *et al.* 2009)

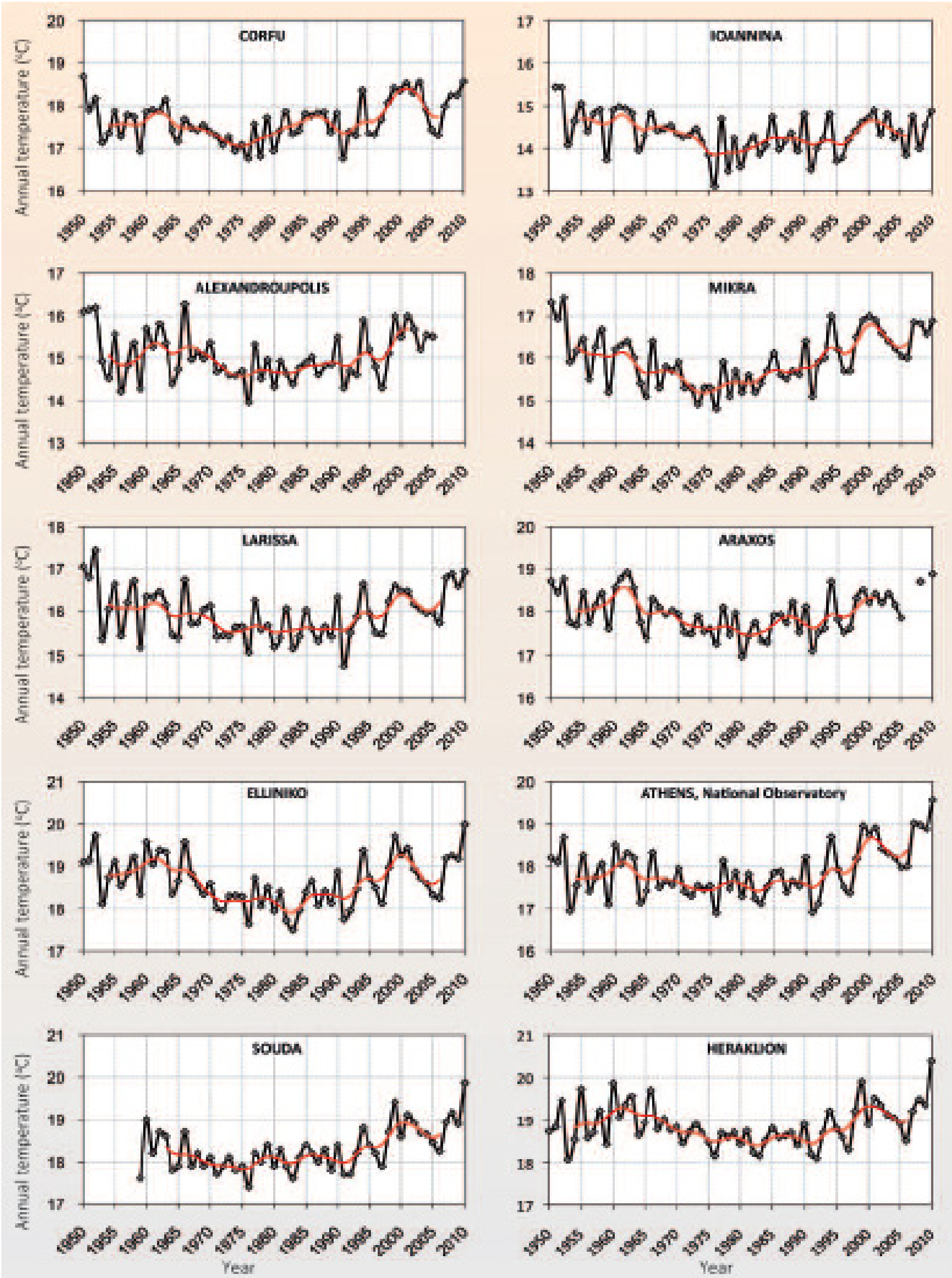


Figure 8. Average annual air temperature period observed at specific Greek stations (1950-2010). Smoothed values illustrated in the red line (Gaussian 9) (Zerefos *et al.* 2011)

II.3.3. Temperature Projections

Greece designates the regions where the minimum winter temperature (Fig. 9) to be around 1.5° C higher for the period 2021 to 2050 and around 3.5° C higher for the period 2071 to 2100, with a reference period from 1961 to 1900. Large-scale recorded findings support the reliability of these results regarding an increasing trend in minimum temperatures over the past decades. Moreover, these results show that the warming trend will be even more noticeable in the mountainous areas, especially in the mountain ranges of Pindos and Northern Greece, where it is expected to reach 2° C from the 2021 to 2050 and 4° C from 2071 to 2100 (Zerefos *et al.* 2011).

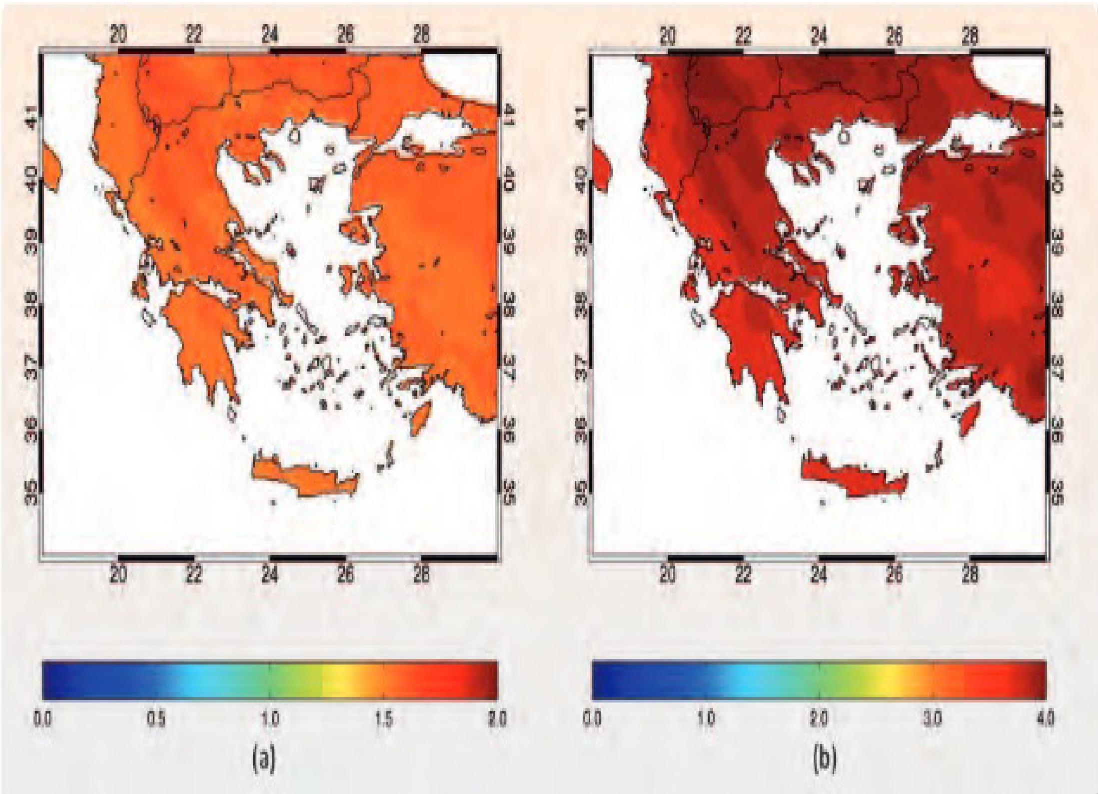


Figure 9. Variation of the average minimum winter temperature in (left) 2021-2050 and (right) 2071-2100, with reference period to 1961-1990 in ⁰C (Zerefos *et al.* 2011)

Average maximum summer temperatures also show an increasing trend. More specific projected changes (Fig. 10) show an increase over the period between 2021 and 2050 that will exceed even the winter minimums and exceed 1.5 °C (under some circumstances it could reach 2.5 °C). Between 2071 and 2100, the increasing trend in mean maximum summer temperatures may be approximately 5 °C. Significantly, the continental inland areas will be affected more than other regions, even though they are located at a greater distance from the sea and its cooling effects. In contrast, regions that present strong sea breezes (Crete, Aegean Islands) estimated that they would experience a significantly lower range in maximum summer temperatures (Zerefos *et al.* 2011).

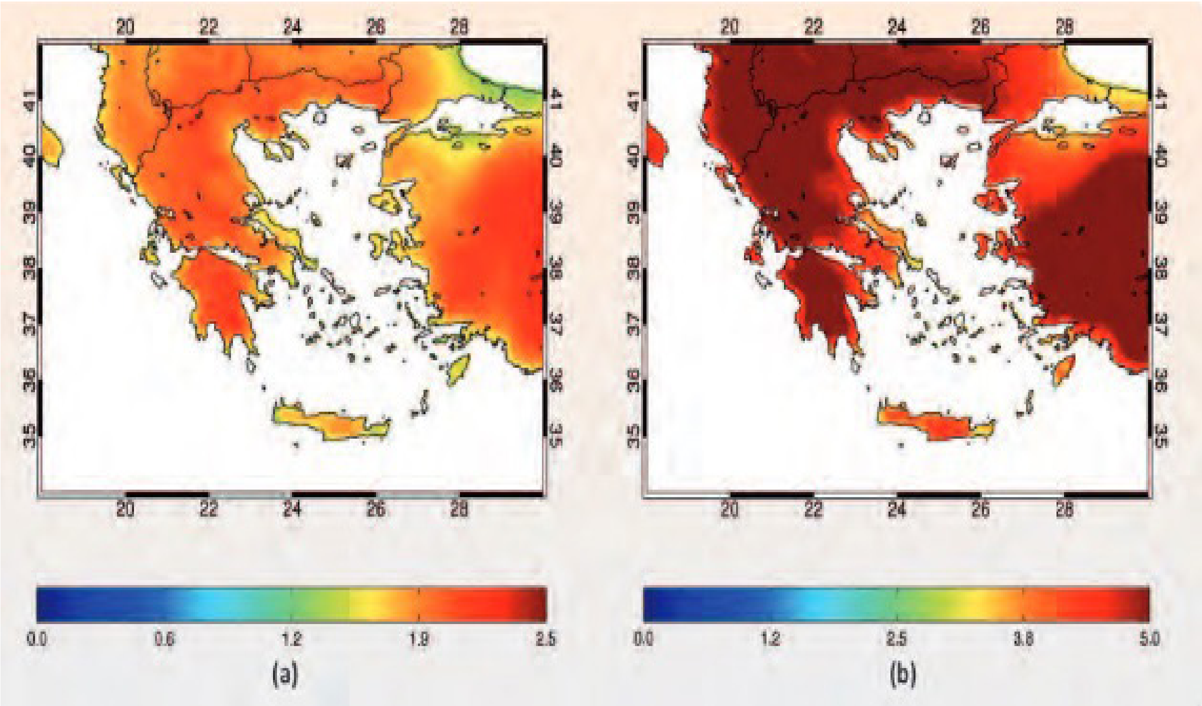


Figure 10. Variation of the average maximum summer temperature in (left) 2021-2050 and (right) 2071-2100, reference period to 1961-1990 in °C (Zerefos *et al.* 2011)

II.3.4. Projections of extreme events

II.3.4.1. Warm Days and Nights

Consider how many days have been recorded with maximum temperatures above the 35 ˚C, illustrated in Figure 11. This projected variation is expected to have a significant impact on human discomfort, especially in urban areas of the continental regions (Central Greece, Thessaly, Southern Peloponnese, Central Macedonia-up to 20 additional hot days are expected per year between 2021 to 2050 and up to 40 in the years from 2071 to 2100). Another result is that the number of hot days in Greece will increase. Milder changes estimated to observed in Crete and Attica (hot days should not exceed 15, yearly from 2021 to 2050 and 30 from 2071 to 2100), and even milder in the Aegean and Ionian regions (10 additional hot days from 2021 to 2050 and 15 from 2071 to 2100, yearly), because of their proximity to the sea and the cooling effect of sea breezes.

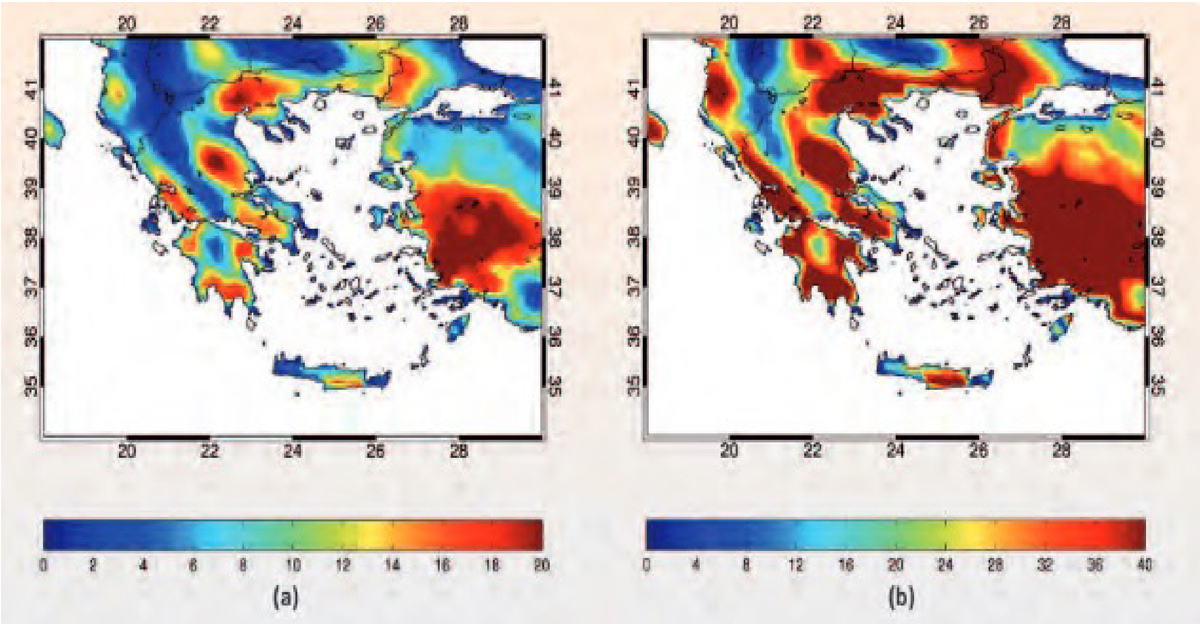


Figure 11. Variation of the days with recorded maximum temperature > 35 °C (left) 2021-2050 and (right) 2071-2100, reference to 1961-1990 (Zerefos *et al.* 2011)

Another essential temperature-related parameter linked to human health is the change in the number of hot nights (consider the number of days with minimum temperature above 20° C). A night qualified as hot (or tropical) if the minimum temperature does not drop below 20° C. A tropical night in combination with a scorching day quickly increases human discomfort and negatively impacts human health. The projections (Fig. 12) show an increasing trend in the number of tropical nights in almost all regions of Greece , with severe characteristics in the coastal and insular areas and milder in continental ones. in particular, Eastern Greece, Crete, and the coastal regions of the Aegean Islands estimated that there would be 40 additional warm nights from 2021 to 2050 and 80 additional warm nights from 2071 to 2100 each year. Furthermore, Eastern Macedonia-Thrace and Western Greece showed an annual increase in the warm nights to be approximately 30 for the period 2021-2050 and 70 for the period 2071-2100; recorded even lower increases projected for Western Macedonia (15 or fewer additional warm nights from 2021 to 2050 and 30 or less from 2071 to 2100, on a yearly base; *Zerefos et al.* 2011).

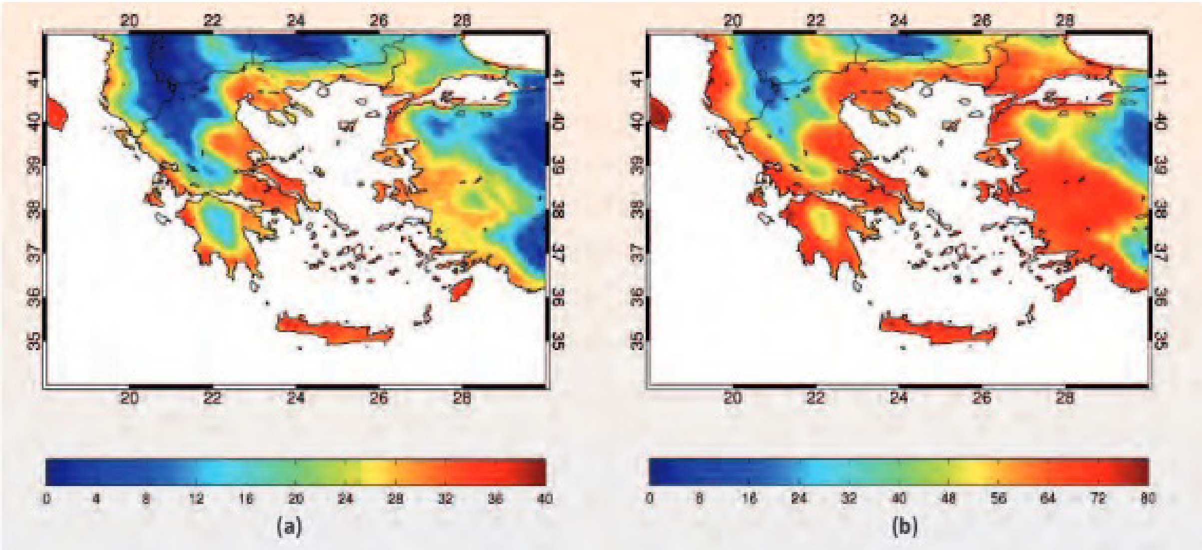


Figure 12. Variation of the days with minimum temperature > 20 ⁰C for the period 2021-2050 and (right) 2071-2100, reference period 1961-1990 (Zerefos *et al.* 2011)

II.3.4.2. Dry Days

The duration of drought periods was also estimated, which would show an upward trend after the projections made concerning the variation in the maximum duration of drought periods (Fig. 13). The western regions of Greece observed lower variations regarding the dry spell length (based on projected results) for the period between 2021 and 2050 (less than 10 more consecutive dry days) and the period between 2071 and 2100 (less than 20 more consecutive dry days). In the Eastern continental regions of Greece (Eastern Central Greece, Eastern Peloponnese, Euboia), the higher increase in dry spell length observed in Northern Crete, which is estimated to have more than 20 additional consecutive dry days for the period between 2021 and 2050, and approximately 40 more consecutive dry days from 2071 to 2100 (Zerefos *et al.* 2011).

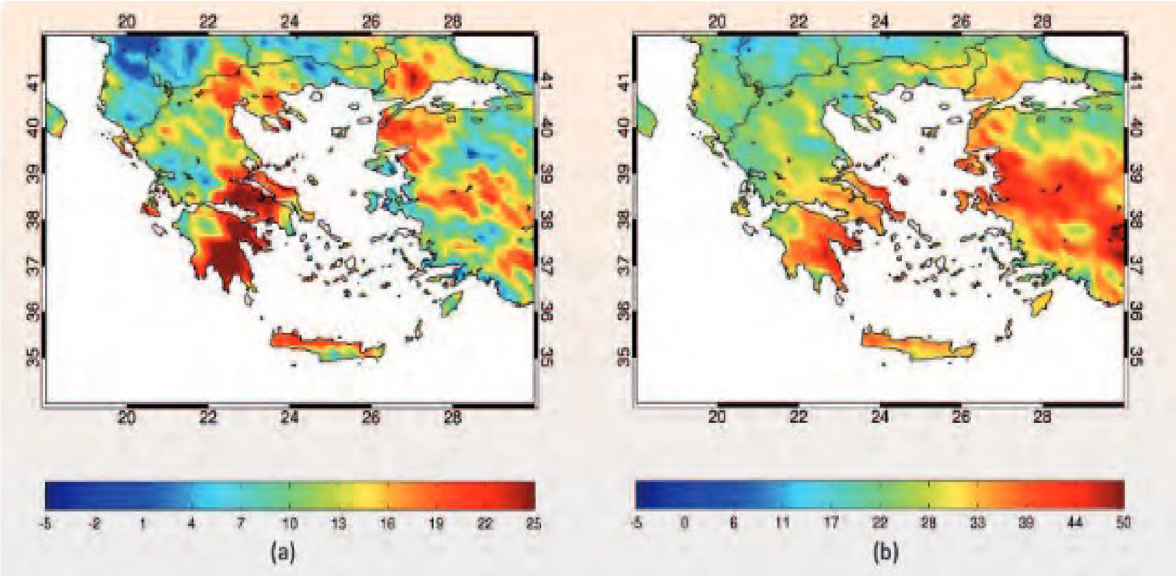


Figure 13. Duration of maximum variation of drought periods (for consecutive dry days) in (left) 2021-2050 and (right) 2071-2100, reference to period 1961-1990 (Zerefos *et al.* 2011)

II.3.4.3. Frost Days

On a yearly basis, the number of frost days (Fig. 14) presents a high interest as an essential parameter, mainly for agricultural regions. The projections indicate a decreasing trend in the Macedonia and Thrace regions, with an estimation of 15 days for 2021 to 2050 and 40 days for 2071 to 2100. In the continental areas of Thessaly and Peloponnese, a decreasing rhythm of about 10 to 15 days from 2021 to 2050 and about 25 days from 2071 to 2100 is observed.

The other regions of Greece show a lower rate of decrease, mainly due to the very small number of recorded frost days that these regions have recently experienced (Zerefos *et al.* 2011).

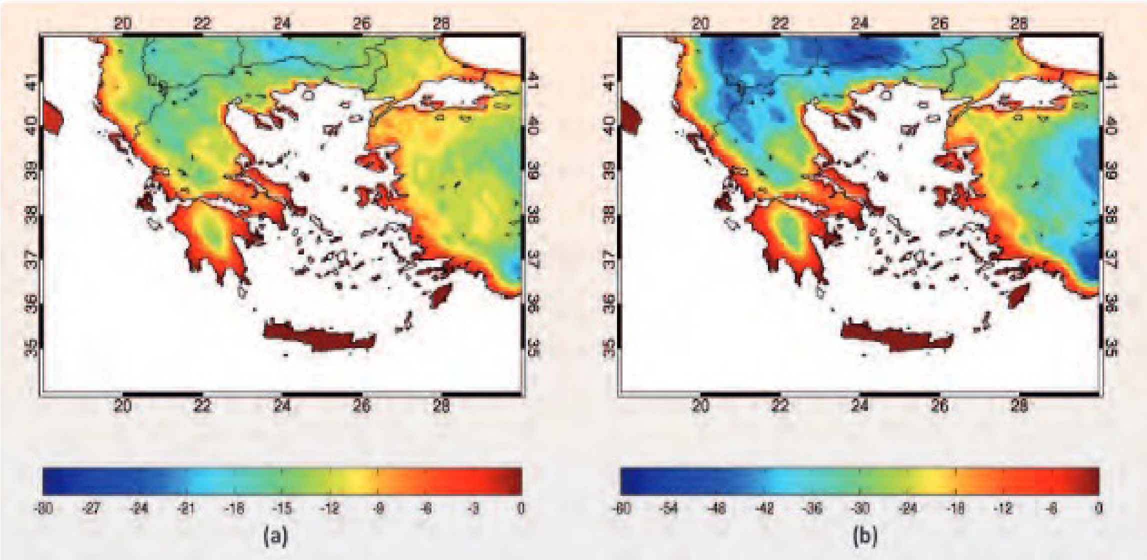


Figure 14. Variation of the night frosts in (right) 2021-2050 and (left) 2071-2100, reference period of 1961-1990 (Zerefos *et al.* 2011)

II.4. Sea Surface Temperature

Sea surface temperature follows the same pattern as atmospheric temperature; he average water temperature is colder in the north (12.5 to 14.0°C) and warmer in the south (19.0 °C to 20.5 °C; Fig. 15).

The western coast of the Aegean Sea is slightly colder than the eastern coast, and the causes are the warm current from Asia Minor on one side and on the other side by the colder current from the Black Sea, which penetrates the Northern Aegean (Metaxas, 1973). SST in Greece is:

- Northern Aegean SST reaches a maximum of approximately 24.0 ˚C in summer (August) and a minimum of 12.5 °C in winter.
- Central Aegean, SST maximum is 25.0 °C in summer, and the minimum is 14.5 °C in winter.
- Southern Aegean, SST maximum is 25.0 °C in summer, and the minimum is 15.5 °C in winter.
- The Ionian Sea SST maximum is 25.5 0C, and the minimum is 15.0 0C.
- The highest average annual SST in Greece is observed in the Island of Rhodes (~20°C), while the lowest mean yearly SST is recorded in the broader area of Alexandroupolis (~15.5 °C).

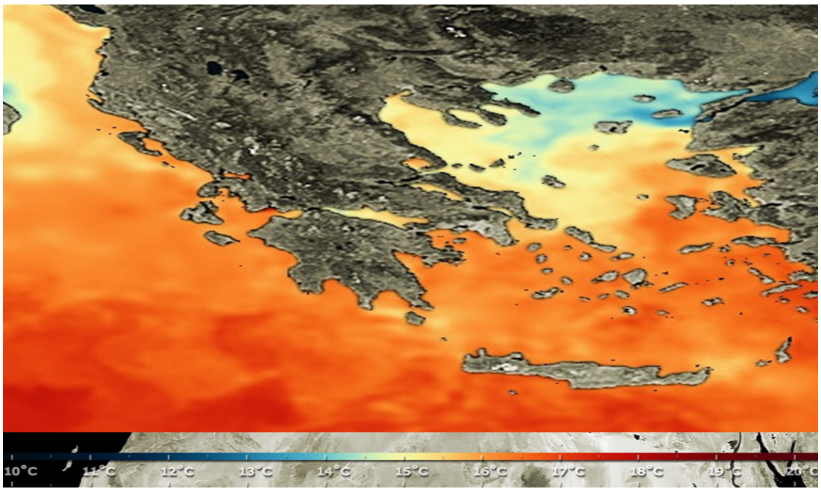


Figure 15. Mean sea temperature (sentinels.copernicus.eu)

II.5. Sea Level Rise

Sea level rise is one of the most serious impacts of climate change (Fig.16). The mechanism behind that is the warming of the oceans, which causes the phenomenon of thermal expansion of marine waters, and then the rise in sea level. In a similar tool, water from land ice melts and ends up in the oceans, causing sea levels to rise. Direct sea level observations and recording, based on the last 100 years, from high-precision altimeter satellites, show that sea level is increasing continuously (Nerem *et al.* 2010), with potentially severe impacts in many lowland regions on the whole planet.

Sea level changes pose a significant threat to coastal areas. Mediterranean Sea projected scenarios for climate change provide almost the same results as global models (IPCC-AR3 and AR4 models). The projection of sea level rise scenarios showed that until 2,100 an average sea level rise between 19 and 58 cm is estimated, depending on the socio-economic assumptions and greenhouse gas emission scenarios (IPCC, 2007). What mainly causes the upward trend of GMSL is the thermal expansion of seawater, the melting of land ice, and the exchange of freshwater masses between the oceans and terrestrial water reservoirs.

In particular, in the Mediterranean Sea (scenario A2) there is enormous spatial variability with a maximum sea level rise of about 25 cm, with lower values in the eastern Mediterranean and higher in the western Mediterranean (Zerbini and Rocco, 2014).

Greece has one of the most extensive coastlines in the world and among all the Mediterranean countries, with an extreme size of 16,300 km coastline, of which approximately 1,000 km characterized as areas with a high vulnerability to climate change, due to the assessment risk of a rise in the average sea level of Greece's surrounding seas between 0.2 m to 2 m until the year 2,100 (Karymbalis, 2017; Fig. 17).

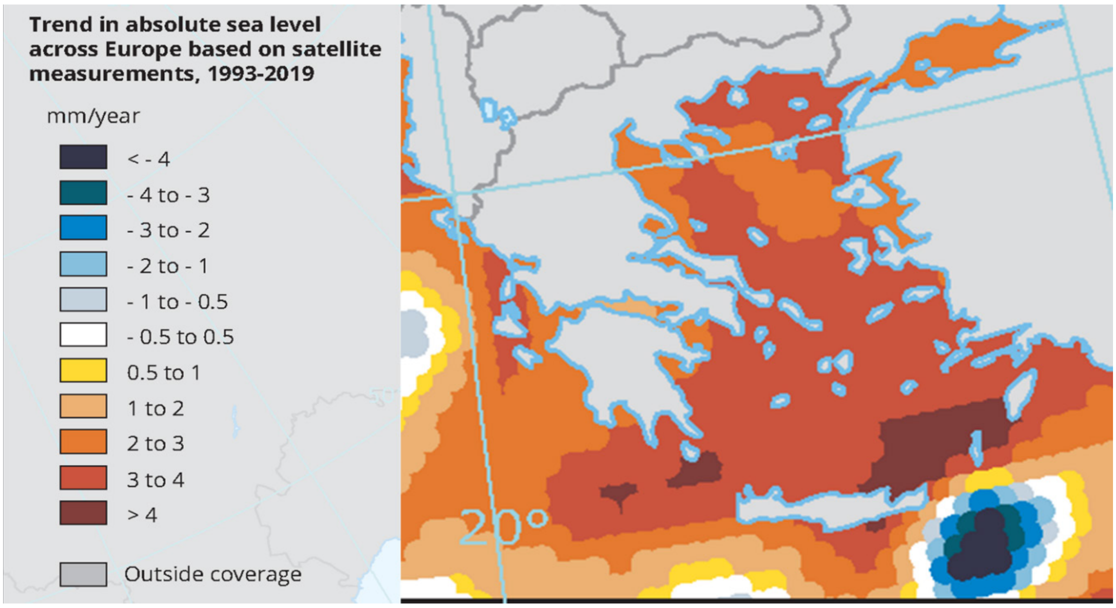


Figure 16. Trends and Spatial distribution of the mean sea level in Greece (period from January 1993 to February 2019) (sentinels.copernicus.eu)

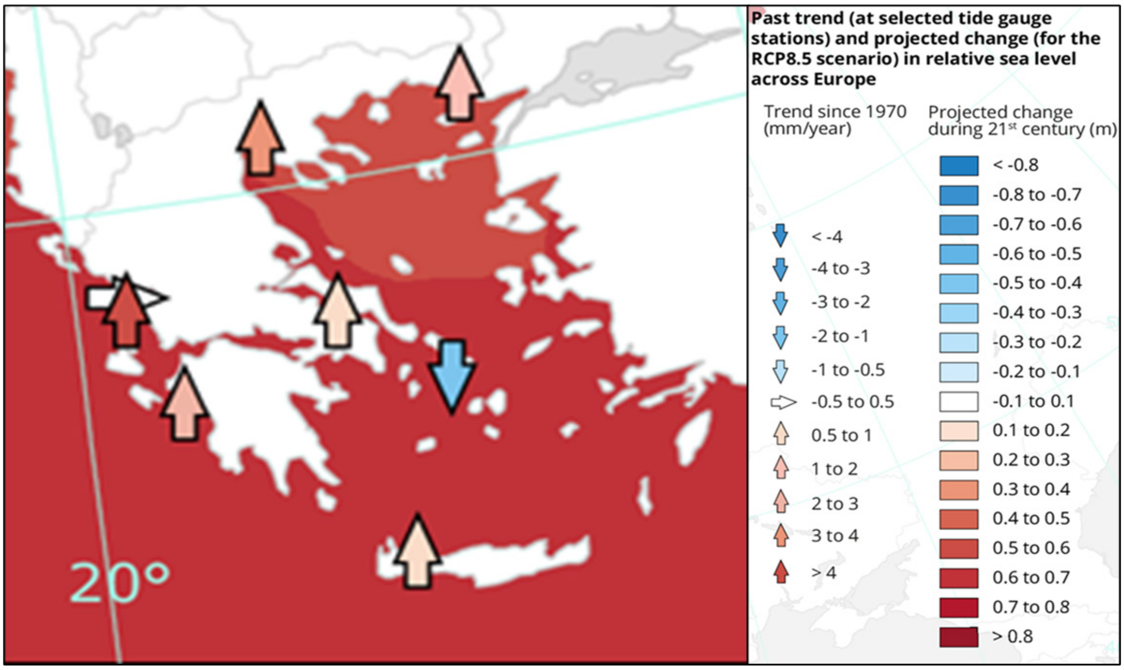


Figure 17. Past Trends and Projected Changes of the sea level in Greece (based on RCP8.5 scenario) (sentinels.copernicus.eu)

III. Morphological Characteristics of Coasts in Greece

III.1. Introduction

In Greece, the coastal zone plays a vital role over history in the country's socio-economic life. Greece has 13 regions (NUTS II). Most of urban areas of Greece are in the coastal zone. With the exception of this coastal area in Greece comprising 80% of general industrial activities, 90% of tourist and recreational activities, most fisheries and coastal ecosystems, 35% high quality and productivity of agricultural land, and the majority of critical infrastructure such as seaports, airports, road and electricity networks, *etc.)* (Lioutas and Tsimopoulou, 2010).

III.2. Characteristics of Coasts Morphology

The geomorphological categorization of Greece coasts is based on the classification of the European program "EROSION" project (2001). According to the project's classification, there are four types of beaches identified in Hellenic coast, from the 6 in total that the project determines (Alexandrakis *et al.* 2014; Lenôtre *et al.* 2004), these are:

1. **Rocky coasts and cliffs made of hard rocks,** which show a low level of erosion and sometimes accompanied by a rocky platform (rugged rocky coasts represent 44% or 6,063 km of the total Greek coasts),
2. **Cliffs made up of conglomerates and soft rocks** (almost chalky) have a low level of erosion, usually with pocket beaches (more than 200 m long), (soft rock cliff or conglomerate coasts with pocket beaches make up 14% or 1,929 km of the total Greek coast)
3. **Beach zones:** it includes

- Short beaches (from 200 to 1,000 meter long) usually separated by rocky capes (more than 200 m long),
- Extensive beaches (less than 1 km long), often with strands of coarse sediment (gravels or pebbles),
- Extensive beaches (less than 1 km long), with strands of fine to coarse sand.
- Non-cohesive soft sediment shorelines such as barriers, spits, tombolo are sometimes included together with artificial and nourished beaches.

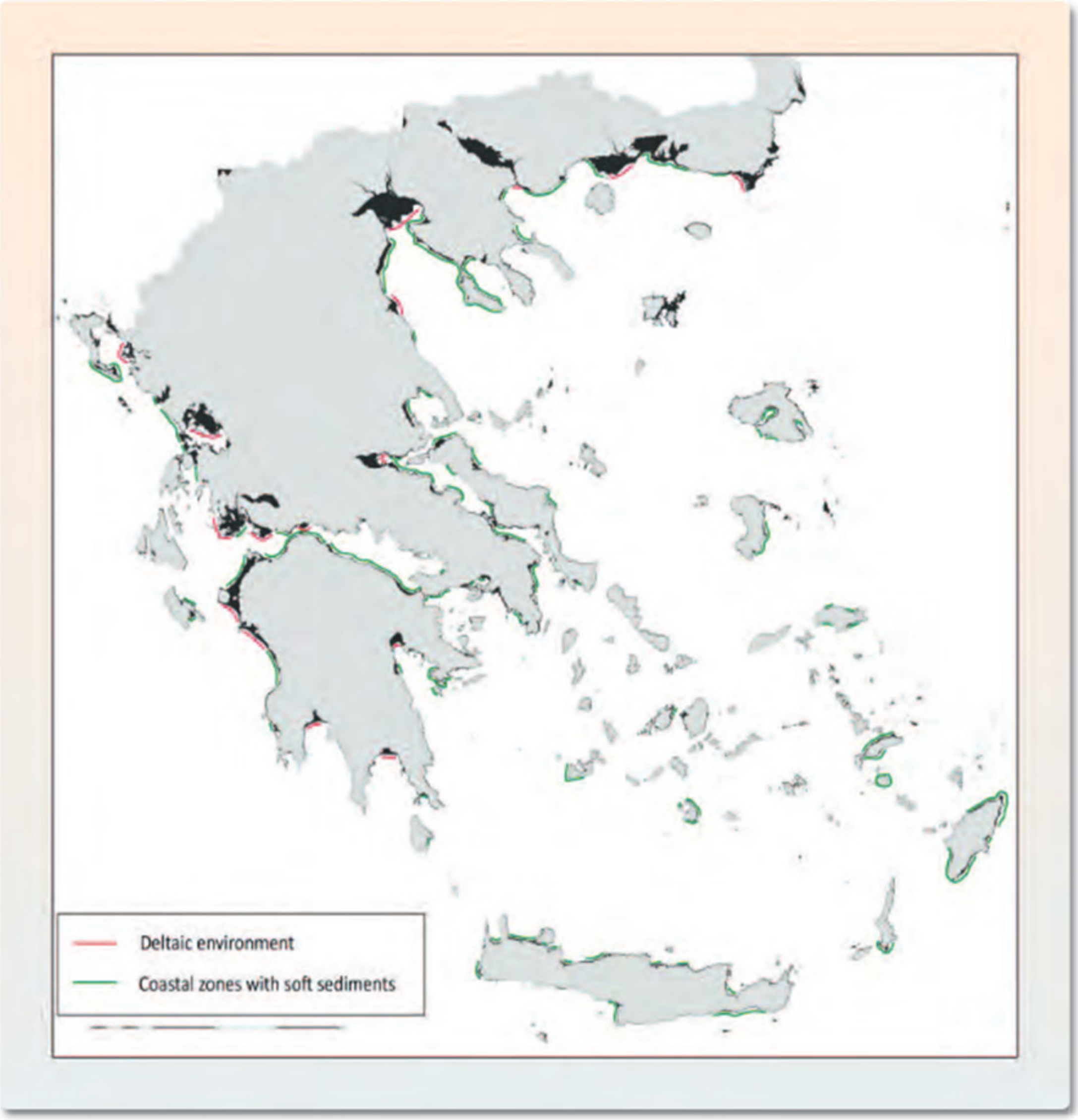
The beach zones consist of 36% or 4,961 km of the total Greece coasts.

4. **Muddy coasts** containing muddy sediments linked to deltaic deposits, and the mud coasts consist of 6% or 827 km, of the entire Greece coast.

Another coastline classification is from a geomorphologic-geodynamic standpoint/ category. Under that categorization Greece's coastline can be classified into the following three main areas (Zerefos *et al.* 2011; Fig. 18):

1. **Deltaic coastal areas. Red-colored areas in** Figure 18, these lowland coastal areas are formed of loose, unconsolidated sediment deposits and present a high level of vulnerability to sea level rise.
2. **Coastal areas consisting of non-consolidated sediments of Neogene and Quaternary age. Green-colored areas, usually low-lying coastal areas, are subject to a type of recessional erosion and have a medium level of vulnerability to sea level rise.**
3. **Rocky coastal areas: The rest of the uncolored areas, these coastal areas in** Figure 18, consist of hard rock of deficient level of vulnerability to erosion, sea level rise, and the main type of Greek coastlines.

Of a total of 16,300 km of Greek coastline, 960 km (6%), is related to deltaic areas with a high level of vulnerability, 2,400 km (15%) is non-consolidated sediments with a medium level of vulnerability. The remaining 12,810 km (79%) are connected to rocky coastal regions of low vulnerability without any color. Overall, the total Greece coastline length, which presented a medium to high-level vulnerability to sea level rise, is approximately 3,360 km or 21% of Greece's coasts.



Greece's coastal areas can be classified into: a) coastal areas of medium vulnerability to sea level rise (in green), usually of low altitude and consisting of soft sediments of the Neogene and Quaternary age; b) coastal areas of high vulnerability to sea level rise (in red), low-lying and formed of deltaic deposits; and c) rocky coastal areas of low vulnerability to sea level rise (black sections) of high altitude.

Figure 18. Greece's coastal –or line classification (Zerefos *et al.* 2011)

IV. Impact of SLR on Greece Coasts

IV.1. Impact of SLR on Coast Stability

Sea level rise scenarios vary, but all show an increasing trend by 2,100. Projections calculated a rise between 0.2 m and 2 m, which means that many coastal areas in Greece are under threat, in the case of the SLR by 1 m. However, it is not scientific to correct an estimation regarding the vulnerability of each of the 12 coast regions based solely on the amount of sea level rise. Predictions and used models should identify and calculate the local factors, which play a role in the accurate calculation of SLR (Fig. 19). These factors are the tectonics, sediment transport (from inland to coast areas), and coastal geomorphology/lithology, which is linked to the vulnerability level in erosion. Tectonic activities in Greece play an important role in SLR where tectonics can decrease or increase by tectonic uplift or subsidence.

Figure 19. Coastlines status in Greece (Satta *et al.* 2017)

Especially in the case of the coastal zone of the Northern Peloponnese, researchers have estimated an elevation rate between 0.3 to 1.5 mm/year, Crete also counted a rise between 0.7 to 4 mm/year, and on the island of Rhodes, a 1.2 to 1.9 mm/year elevation. These factors greatly affect the final number of the SLR and significantly reduce the average SLR value from 4.3 mm/year to 3.5 mm/year, after the reaction of a mean tectonic elevation of 0.8 mm/year. On the other hand, an increase in sediment vacation and deposition in large river delta-front water bodies causes the delta front to advance and locally counterbalance the SLR (Satta *et al.* 2017).

In addition, a decrease in a river or stream sediment vacation could reinforce the invasion of the sea resulting from the sea level rise. Lastly, the coast's morphology plays a vital role in coast vulnerability to sea level rise, in particular the slope and the lithological synthesis, which are directly linked to the levels of erosion. An erosion degree can vary, from a very high degree when there are coastlines with lowland geomorphology and vulnerably to erosion lithology composition (several meters yearly), to a meager degree in the case of hard coastal limestone formations (mms yearly) (Zerefos *et al.* 2011).

IV.2. Submergence of Lowlands

Table 2 illustrates the estimations regarding the coastline retreat due to SLR. Moreover, it presents the approximate values of flooded coastal areas and coastline retreat (without considering tectonic and geodynamic effects). Based on the projected SLR of 0.5 m and 1 m; respectively, in 3 high-risk deltaic areas, the Axios, Aliakmon, and Alfeios river deltas (Poulos *et al.* 2009). The prediction of the coastline retreat scaled between 30 m and 2,750 m in response to a potential sea level rise of 0.5 m and between 400 m and 6,500 m in response to an increase of 1 m of the sea level. Evaluating the severity of a SLR impact on coastal regions includes a group of uncertainty, regarding:

(a) The tension of the SLR, based on projections scaled between 0.2 m and 2 m.

The sea will rise depending on many factors, both physical, notably the astronomical forcing, and human-made (greenhouse gases).

(a) The relationship between tectonic uplift and eustatic SLR.

In many parts of Greece, the high tectonic altitude could be locally counterbalanced and even exceed the eustatic SLR in some cases.

(a) Geological and climatic conditions

They cause the sedimentation of clastic materials in coastal areas; even more, they can be caused by anthropogenic intervention (e.g., dams, river sand mining). For example, in the case of river deltas, these factors potentially change their vulnerability to sea level rise.

Table 2. Estimated shoreline retreat (in m) and coastal flood from a projected sea level rise of 0.5 m and 1 m, for various deltaic areas of Thermaikos and Kyparissiakos Gulf (Poulos *et al.* 2009)

Coastal area	Sea-level rise (m)	Coastline retreat, Bruun's model (m)	Coastline retreat due to sea-level rise (m)	Coastline retreat due to coast erosion (m)	Total coastline retreat (m)	Inundated area (km²)
Alfeios Delta (northern part)	0.5	51.1	175	15	190	224
	1.0	102.2	810	-110	700	683
Alfeios Delta (southern part)	0.5	54.5	15-30	0-15	30	35
	1.0	109.0	10-100	400	400-450	344
Axios Delta	0.5	52.7	250-2,000	0	250-2,000	10,825
	1.0	213.6	2.000-2,500	0	2,000-2,500	28,482
Aliakmon Delta	0.5	63.6	50-1,750	0	50-1,750	4,875
	1.0	195.4	250-2,500	0	250-2,500	8,950
Deltaic plain of Loudias-Aliakmonas	0.5		500-2,750	0	500-2,750	8,900
	1.0		5,000-6,500	0	5,000-6,500	25,575

IV.3. Beaches Erosion

Beaches are the heart of the economy for many countries, especially in the Mediterranean Sea. Coastal erosion of beaches and low-lying shorelines is a serious concern for many countries, threatening except the economies of the countries, other sectors such as the natural environment, industrial capacity, transport, and cultural heritage. A combination of anthropogenic and physical factors can cause erosion, which is numerous and complex in calculations. These factors could be variations or fluctuations in wave energy, tidal currents, wind action, the nature and origin of sediments, and sea level rise. SLR predicted effects on the sustainability of the future coastline, is a challenge to assessing its impact (National Climate Change Adaptation Ctrategy , 2016).

Hotspots are considered coastal areas that bring together the required factors that can lead to erosion at different levels for each area (Fig. 20). The impacts of corrosion and the elements at risk are classified according to different levels/degrees. An indicator of this categorization is whether a coastal defense structure successfully achieves its objectives. These degrees are:

1st Degree

A first-degree erosion hotspot is defined as a coastal area when erosion is noticeable on the coastline despite the presence of protective structures in combination with values at risk in the inland of the coast.

2nd Degree

The appearance of erosion characterizes a second-degree erosion hotspot but without any defense works at the coastline.

3rd Degree

The third degree of erosion hotspot is the appearance of places where the shore is in a stable situation. at the same time, some beaches are artificially maintained for an obvious erosion problem.

4th Degree

A fourth-degree erosion hotspot is a particular case in which cumulation reveals a threat to existing wetlands.

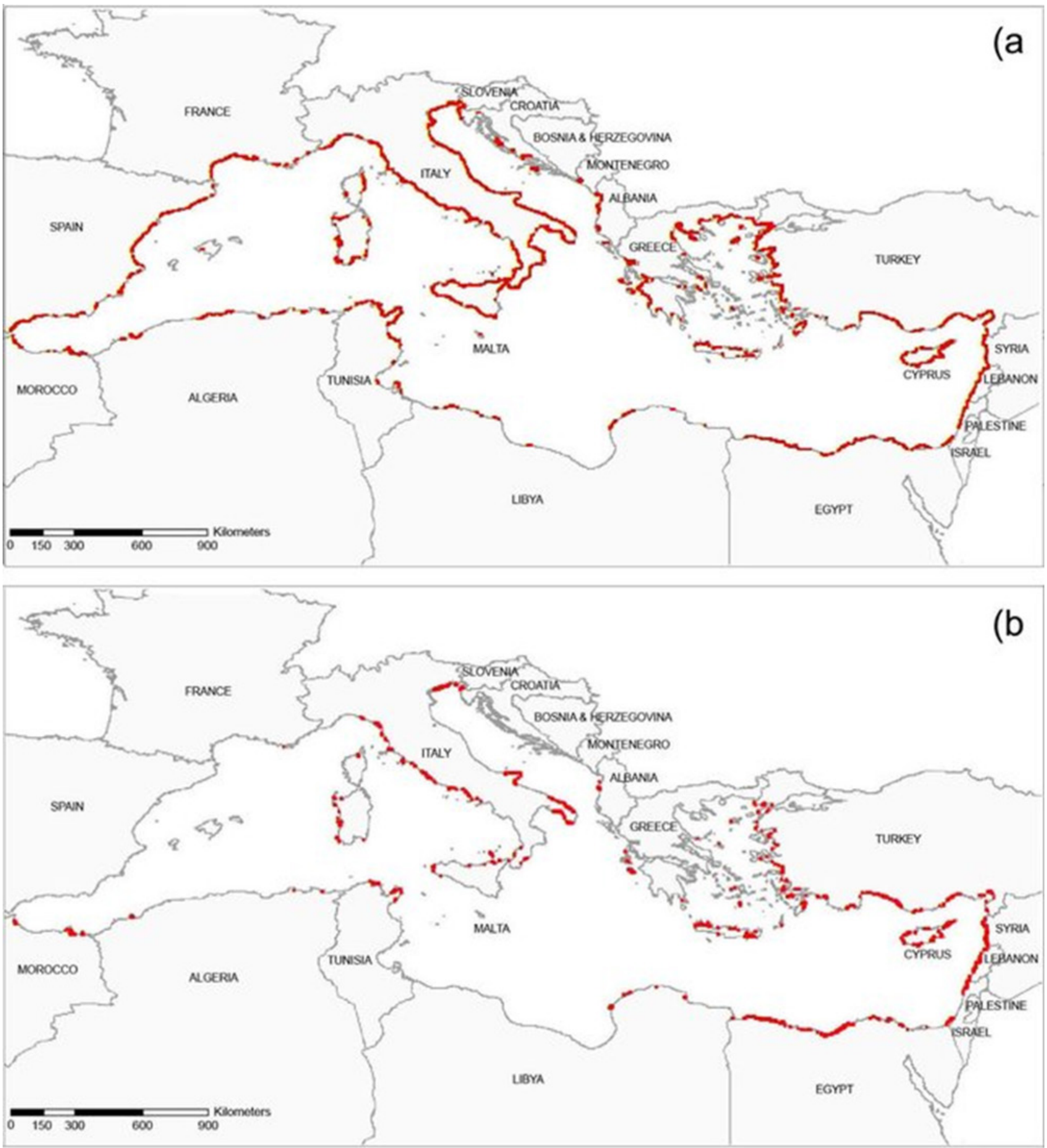


Figure 20. Hot Spots' Analysis maps, (upper map) Fixed Distance Band (bottom map) Inverse Distance (Satta *et al.* 2017)

The vital priority is the prediction of sea level rise and coastline retreat, resulting in population accumulation in coastal areas (Fig. 21). The balance sheet is much more difficult on coasts with high density and increasing human activities, especially considering the unfacilitated/uncontrolled mass tourism areas.

As highlighted, the primary threat to the Greek Coasts and Beaches is coastal erosion, especially beach erosion, which is now more apparent than ever before that is considered an imperative threat for the local and national economy. The factors that govern the processes of beach erosion are natural and artificial, following two types of hazards: a loss of land and/or distraction/degradation of the coastal ecosystem, with negative economic outcome undermining coastal areas' substructures.

Coastal erosion (Figure 22) is defined as the loss of coastal material relative to a standard baseline. Erosion is considered a complex natural phenomenon because it is caused by a huge variety of natural processes combined with anthropogenic activities, which have spatiotemporal characteristics (Berriolo *et al.* 2001; Khalil, 1997; Medina and Lopez, 1997; Pranzini and Rossi, 1995)

The main characteristics of beach zones regarding the control of coastal erosion can be:

- Beach and shore zone slope.
- Coast lithology.
- Shore wave regime.
- Frequency of storm events.
- Human-made interventions.

Research shows that the vulnerability of Greece coasts (Petrakis, *et al.* 2014) is due to:

- The coast geomorphology
- The coastal slopes
- The average wave heights
- The average tide ranges
- The referential sea-level rise
- The anthropogenic interventions

A representative example of the coasts' erosion in Greece is the island of Cretan, the beach is under extended erosion (Table 3)., estimated that more than 65% of the shoreline is retreating, when the estimated primary percent of total Greece's coastline is not more than 30% (Robinson and Cardozo, 2001; EROSION, 2001). The extremely high quantity of eroding coastline in Crete is linked to its extended beach zones (Alexandrakis *et al.* 2006). Also, measurements have shown that all the northern coast of Crete presents the highest vulnerability to erosion in Greece (Petrakis *et al.* 2013).

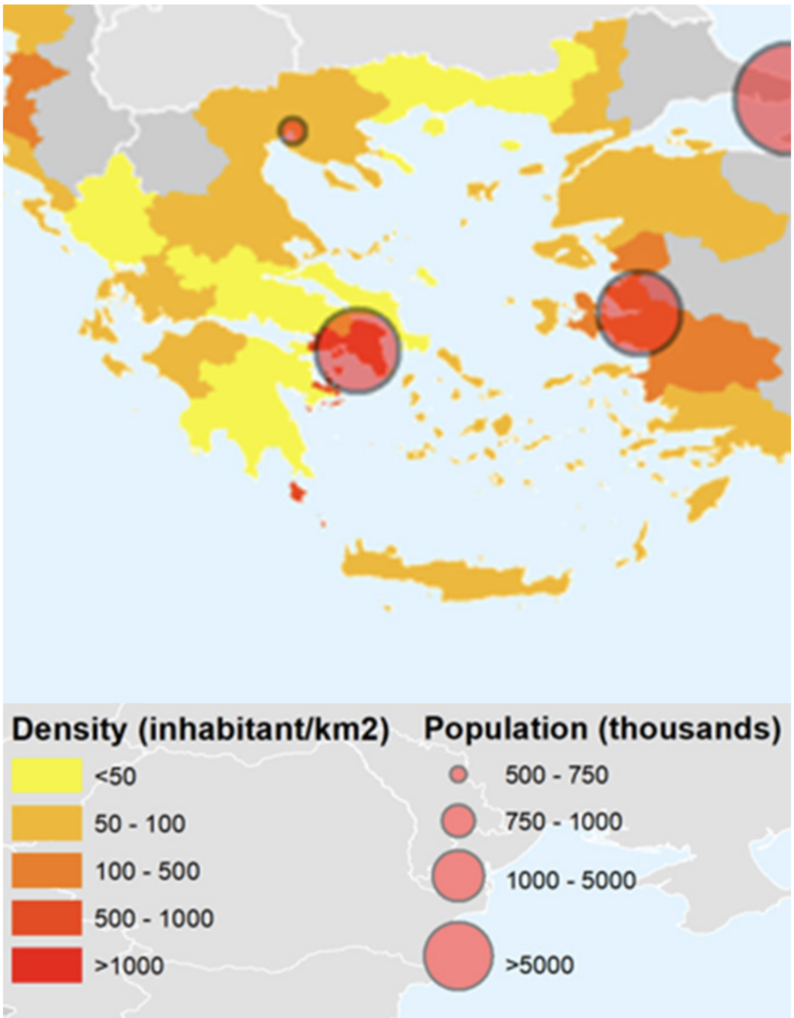


Figure 22. Population density in Greece coastal areas (Plan Bleu from various sources)

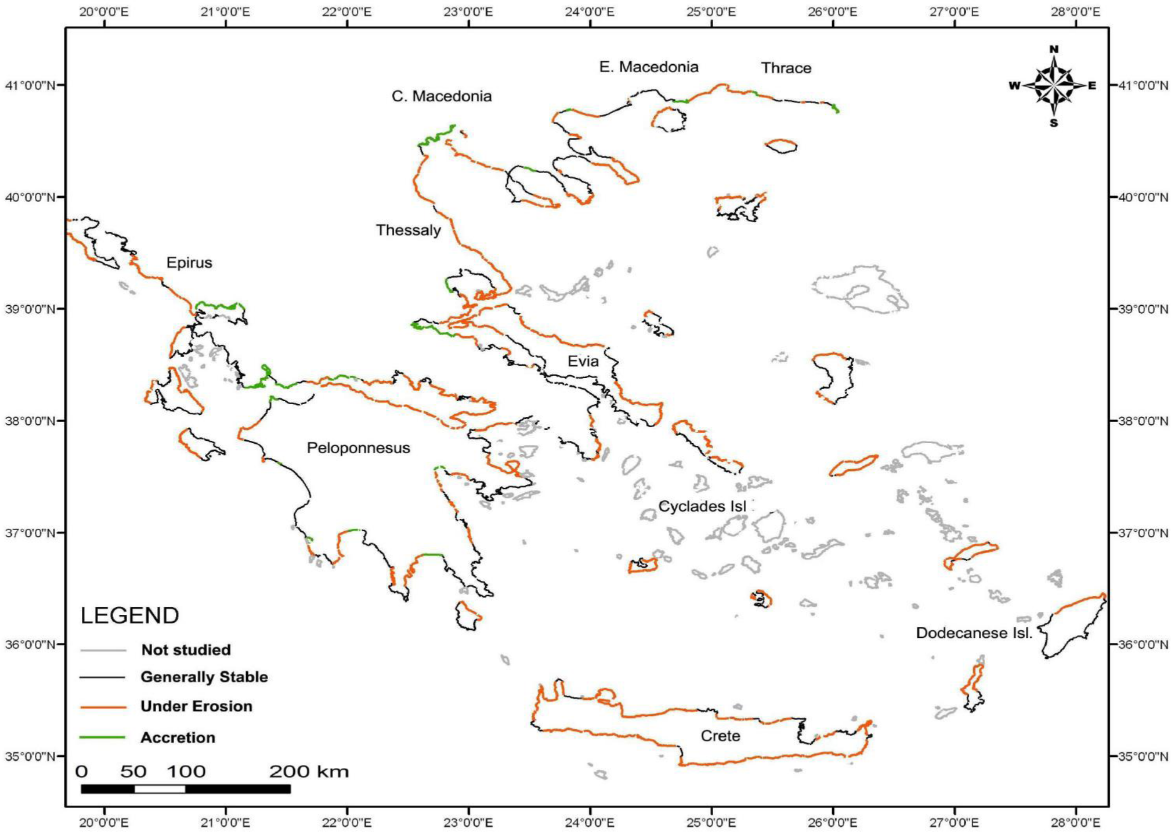


Figure 23. Current evolutionary trends in Greece's coastlines (Petrakis *et al.* 2014)

Table 3. Percentages of receding coastal area in Greece (after Alexandrakis *et al.* 2006)

Area	Retreat percentage
Thrace and East Macedonia	6.1%
Central Macedonia	10.3%
Thessaly	2.3%
North Aegean Islands	14.7%
Attica	10.8%
Cyclades and Dodecanese islands	25.9%
Peloponnesus	3.8%
Northern coast of Crete	6.1%
TOTAL	80.0%

IV.4. Coastal Zones and Touristic Areas

Tourism is important for the Greek economy. The fact that 12 of Greece's 13 regions are coastal areas (only one is landlocked) proves the vital role of coastal areas in Greece. The coastal regions of Greece facilitate almost the vast majority of tourist and local activities. In 2018, touristic products were estimated to directly contribute to the national economy of approximately €15.1 billion (UNWTO, 2018).

Tourism plays an essential role for the economic and social development of Greece, taking under consideration that it is one of the best 20 tourist destinations globally. Accordingly, the preservation of Greek beach areas is of paramount importance, as their quality depends on the economic future of the country (Anastassopoulos *et al.* 2009).

V. Climate change and morphological stability parameters

As part of the Co-Evolve4BG project, various parameters have been developed to provide an inventory of the evolution trend of coastal areas at both national and Mediterranean scales in the light of Climate Change. This set is composed of 5 parameters, as presented in Table 4.

Table 4. Climate change and morphological stability parameters as part of the Co-Evolve4BG project

Parameters	Variable	Description	Source
Coastal evolution	Erosion (km)	Coastal erosion defined as the loss or displacement of land mass or the long-term removal of sediments and rocks along the coastline	RISES-AM project
	Stable (km)	Coastal stability is the absence of loss or displacement of land	RISES-AM project
	Progradation (km)	Progradation is the growth of the coast further out to sea over time.	RISES-AM project
	Coastal erosion rate (mm/year)	Rate of erosion process by the time	RISES-AM project
	Coastal stability rate (mm/year)	Rate of stability process by the time	RISES-AM project
	Coastal Aggregation rate (mm/year)	Rate of aggregation process by the time	RISES-AM project
Type of coastline	Rocky (km)	Tidal zone of seacoasts where solid rock predominates.	RISES-AM project
	Sandy (km)	Sandy shores or beaches are loose deposits of sand, including some gravel or shells, covering the shoreline in many places.	RISES-AM project
	Cliff (km)	It is a steeply sloping surface where elevated land meets the shoreline.	-
	Dune (km)	It is a landform composed of wind-driven sand.	-
	Coastal marshes (km)	Coastal ecosystems in high tide zones. The area between land and open salt or brackish water, which is frequently inundated by the tides.	RISES-AM project

Water temperature	Average water temperature (°C)	The current mean annual value of seawater temperature.	Hellenic Centre for Marine Research
	The water temperature rises (°C/Year)	Rate of seawater temperature increase per year.	Hellenic Centre for Marine Research
Sea Level Rise	Max Sea Level (cm NGT)	Current maximum sea level	Hellenic Centre for Marine Research
	Sea Level Rise (cm/Year)	Sea level rise in one year. Satellite altimetry data provides accurate measures for a limited time range expressed in cm/y.	Hellenic Centre for Marine Research
Atmospheric temperature	Atmospheric temperature (°C)	The current average annual value of atmospheric temperature.	Hellenic National Meteorological Service
	Atmospheric temperature rise (°C/Year)	Rate of atmospheric temperature rising per year.	-

VI. Conclusions

This bibliographical feedback highlights the main climatic conditions and morphological characteristics of Greece's coastline. It identifies the main challenges and emerging threats to the sustainability of Greece's coastal areas concerning anticipating climate change.

Greece a surrounded by the Mediterranean Sea and characterized by the Mediterranean climate. The climate characteristics vary, with mild and wet winters in the low-lying southern regions of the country and island areas. The other region is characterized by cold winters and heavy snowfall in the central and northern mountainous regions with hot and dry summers. Greece has one of the longest coastlines in the world, with 16,300 km of coastline, of which around 1,000 km are areas characterized as highly vulnerable to climate change (Climate change, 2014).

In Greece, the coastal zone has for years played a vital role in the socio-economic life of the country. Most of the main urban areas of the country are in the coastal zone. Except that the coastal zone in Greece gathers 80% of the general industrial activities, 90% of touristic activities and recreation, most of the fisheries and coastal ecosystems, 35% high quality and productivity of agricultural land and most critical infrastructure such as seaports, airports, road and electricity networks, *etc.* (Lioutas and Tsimopoulou, 2010).

Tourism is of paramount importance for the Greek economy. The fact that 12 of the 13 Greek regions are characterized as coastal (only one is landlocked) proves the vital role of coastal areas in Greece. The coastal regions of Greece facilitate almost the vast majority of tourist and local activities.

Estimated total ~16,300 km of Greek coastline, 960 km (6%) correspond to deltaic areas with high vulnerability, 2,400 km (15%) correspond to non-consolidated sediments of medium vulnerability and the remaining 12,810 km (79%) correspond to rocky coastal regions with low vulnerability. As a result, the total length of the Greek coastline with medium to high vulnerability to SLR amounts to 3,360 km, or 21% of the entire Greek coastline.

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