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Snow Cover and Depth Climatology and Trends in Greece

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Abstract: The rising surface temperatures driven by climate change have resulted in significant reductions in snow depth and snow cover duration globally, with pronounced impacts on snow-dependent regions. This study focuses on Greece, a region where snow plays a critical role in water resources and winter tourism. Using numerical model reanalysis data spanning from 1991 to 2020, this study identifies statistically significant declining trends in snow depth and duration of snow cover across much of the country. The findings reveal considerable spatial and temporal variability, with the most pronounced reductions occurring in winter months and mountainous regions. Particularly affected are the northern and central mountainous areas, where snow cover days have decreased by up to 1.5 days per year. Ski resorts at lower elevations exhibit steeper declines in snow reliability compared to higher-altitude resorts, posing challenges to winter tourism. These trends underscore the urgency of adaptation strategies for climate resilience in snow-dependent sectors and the broader implications for water resource management in the region.

Keywords: snow; climate; trends; Greece

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Academic Editor: Daniele Bocchiola

Received: 2 January 2025
Revised: 23 January 2025
Accepted: 31 January 2025
Published: 6 February 2025

Citation: Masloumidis, I.; Dafis, S.; Kyros, G.; Lagouvardos, K.; Kotroni, V. Snow Cover and Depth Climatology and Trends in Greece. *Climate* **2025**, *13*, 34. https://doi.org/10.3390/cli13020034

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1. Introduction

Snow cover is highly responsive to variations in precipitation and temperature, which are the primary factors influencing snowfall, snow cover, and snowmelt. These changes are evident across multiple temporal scales, ranging from short-term weather events to long-term monthly and seasonal climate patterns [1], and result in significant spatial and temporal variability in the distribution of snow mass [2]. Meltwater from seasonal snow is crucial for replenishing essential freshwater resources. In most Northern Hemisphere land regions, annual runoff is predominantly driven by snowmelt [3]. As the climate warms, there are regionally and temporally nonuniform changes in snow cover, snowmelt, runoff, and precipitation patterns [4–7]. In addition to supplying water, seasonal snow cover plays a critical role in the global energy cycle by cooling near-surface temperatures [8]. Variations in snow mass have profound effects on snow-dependent ecosystems, human populations, and economic activities, even in neighboring regions which are snow-free [1]. Moreover, by insulating the underlying soil and affecting vegetation phenology and fire risk, seasonal snow exerts a significant influence on carbon-cycle processes [9].

Snow is the foundation for winter sports and affects the operation of ski resorts, which are major contributors to local and regional economies. Based on data from 2017, approximately 350 million people globally visit ski resorts each year, underscoring the scale and importance of this market segment, particularly for Europe's mountainous areas, where

winter tourism drives regional economies but depends heavily on favorable snow conditions, whether natural or artificially produced [10]. Numerous studies over recent decades indicate that climate change significantly threatens European ski tourism [10–12]. Rising temperatures and diminishing natural snowfall, especially at lower altitudes, are projected to substantially reduce ski seasons by as early as the 2030s, with cascading impacts on employment in winter-related industries and real estate values for holiday properties [10]. Research focusing on Slovak ski areas, for instance, estimated a 6% decline in ticket sales with a 1 °C temperature increase, with potential losses reaching 19% under high-emission scenarios predicting a 3.2 °C increase [13]. The IPCC's Sixth Assessment Report also highlighted research gaps regarding European ski tourism, particularly in Eastern Europe, where comprehensive climatological studies on snow availability are scarce [14].

Ref. [15] assessed the cryosphere's status across Europe and found significant warming and glacial retreat, particularly in Southern and Eastern Europe, including Southeast Europe and the Balkans. The same study highlighted the increased vulnerability of these areas due to thinner snowpack and shorter snow seasons, exacerbating challenges for ski tourism and water resources. The review emphasized the need for region-specific adaptation strategies to address rapid climate shifts and their socioeconomic impacts on tourism and local communities.

The most recent pan-European analysis on the effects of climate change on winter tourism, part of the Copernicus Climate Change Services' "European Tourism" SIS, incorporated reanalysis data from 1960 to 2015 [16]. This study revealed pronounced annual fluctuations in snow conditions and forecasted a notable decrease in snow depth across European mountain ranges over the 21st century, irrespective of specific climate scenarios. Regarding Greece, a recent study evaluated the impact of climate change on ski tourism in Greece, focusing on the Parnassos Ski Resort under scenario RCP 4.5 [17]. Findings for 2051–2060 (compared to 1971–1980) indicated a significant rise in temperature and reduced snow cover, limiting the number of snowy days and potential hours for snowmaking. This poses substantial risks to ski tourism sustainability in Greece.

Despite terrestrial snow being recognized as an Essential Climate Variable (ECV) by the World Meteorological Organization's (WMO) Global Climate Observing System (GCOS) [18], Greece still lacks a comprehensive and systematic ground-based observational network for monitoring snow. The lack of accurate knowledge of snow cover and mass creates a series of problems, such as, among others, inaccurate estimates of freshwater availability and the lack of accurate initial and boundary conditions for hydrological models, which are important tools to minimize the impact of potentially hazardous flood events. Moreover, in operational weather prediction, insufficient data on snow mass diminish the accuracy of weather forecasts at local and regional scales due to land–atmosphere feedback [19]. For climate modeling, it is critical to quantify snow–atmosphere interactions through precise observations and the modeling of energy and mass exchanges [20].

In this current study, we investigate trends in natural snow cover and depth in Greece during the most recent 30-year period, spanning from 1991 to 2020, using numerical reanalysis data. This paper is structured as follows: Section 2 presents the datasets and methods followed by the presentation of the results in Section 3, while the final two sections are devoted to the discussion of the results and the presentation of some concluding remarks.

2. Materials and Methods

This study focused on an area of Greece within a bounding box with coordinates 34.5° to 42° N and 18.8° to 30° E. Figure 1 illustrates Greece's main topographical characteristics and its key geographical regions and ski centers, which are referenced in later sections of this study. Positioned in Southeastern Europe, Greece features a diverse climate heavily

influenced by its geographical location, varied landscapes, and the Mediterranean Sea. Three primary climate zones characterize Greece: the Mediterranean climate with hot, dry summers and mild, wet winters [20,21]; the Alpine climate in mountainous areas, with lower temperatures and heavy snowfall in the winter; and the temperate climate found in northern regions, featuring more balanced seasonal variations. The geographical and topographical features across Greece result in localized climate variations, particularly in mountainous and coastal regions [22].

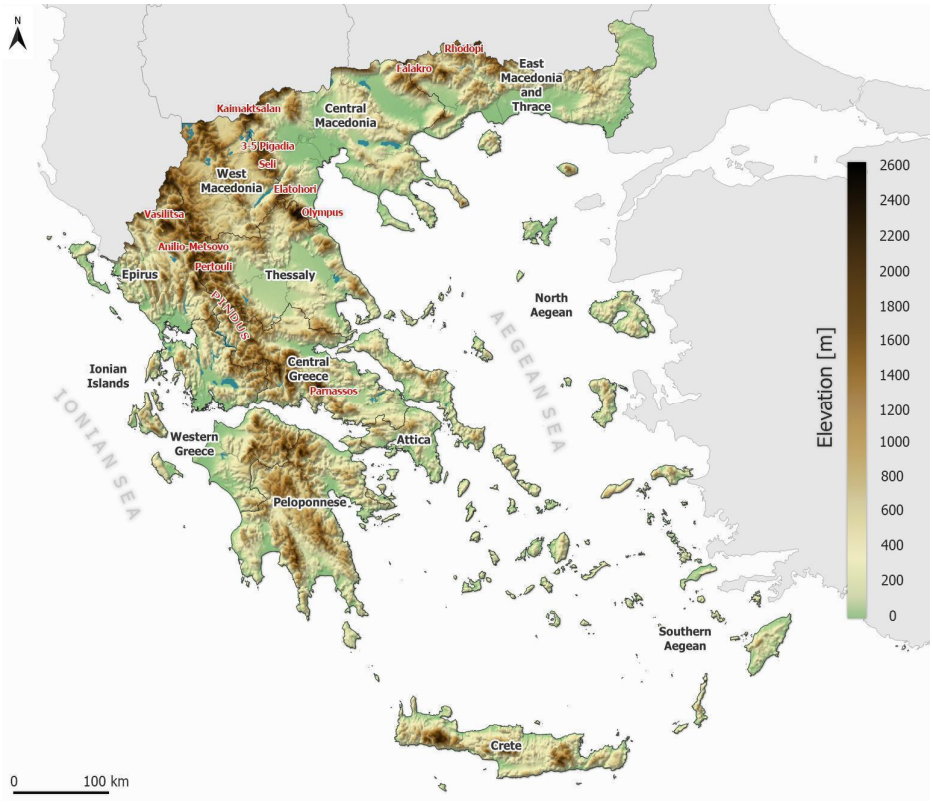


Figure 1. Topographic map of Greece with elevation in meters (shade). The main topographic features mentioned in the text are annotated in black font, while the ski centers and mountain ranges are annotated in red font.

The datasets used for the current study included snow cover and depth data from the regional land surface reanalysis product Copernicus European Regional RE-Analysis Land (CERRA-Land) [23]. This dataset was used to construct the 30-year climatology and analysis trends. The CERRA-Land dataset was provided at a spatial resolution of 5.5 km. The credibility of the snow cover data provided by CERRA-Land was assessed by performing a comparison with the daily snow cover from the Interactive Multisensor Snow and Ice Mapping System (IMS) [24] provided by the National Oceanic and Atmospheric Administration's National Environmental Satellite Data and Information Service (NOAA/NESDIS) and available at a 4 km resolution [25,26]. The comparison was performed for the common period of 2005–2020 for the two datasets. It was found that both the CERRA-Land and IMS datasets showed a consistent behavior regarding the geographical distribution of snow cover over the Greek territory. Regarding the CERRA-Land snow depth data, a recent publication over the Alps demonstrated that this dataset was able to provide a satisfying description of monthly snow evolution [27]. Based on these assessments, we believed that the CERRA-Land dataset was reliable and could be used for the snow climatology analyses performed in the frame of this work.

The climatological analysis presented herein was performed using daily maximum snow cover and snow depth provided by CERRA-Land. For this analysis, a snow cover

day was defined as a day with a maximum daily snow depth greater than 0 cm. The monthly, seasonal, and decadal trends were also calculated, while the statistical significance of the results was also tested. To estimate the trend's slope, a linear regression was applied using the Theil–Sen non-parametric approach. Additionally, the Mann–Kendall (MK) non-parametric test was used to evaluate significance, set at a 95% confidence level. This analysis was performed for the whole Greek domain but also on grid points that fell at or near ski centers [28].

3. Results

3.1. Snow Cover Climatology

The snow cover climatology for Greece, depicted in Figure 2, reveals that the highest number of snow cover days occurs in the Pindus Mountain range, the Olympus Mountain, and the highest parts of the Rhodopi Mountain range, where snow cover persists for up to 130 days per year on average. These regions, situated at higher altitudes, experience prolonged snow accumulation due to the colder prevailing temperatures and favorable topographic conditions. Several other mountainous areas in Continental Greece, including those in central and northern regions, as well as on the island of Crete, also record significant snow cover. These areas typically experience more than two months of snow cover annually, with persistent snow found at elevations higher than approximately 1500 m. The spatial distribution highlights the critical role of elevation and geographic positioning in determining snow retention, with higher-altitude regions acting as snow reservoirs. Lower-altitude and coastal areas show minimal or negligible snow cover days, reflecting the influence of milder winter conditions and less frequent snowfall events.

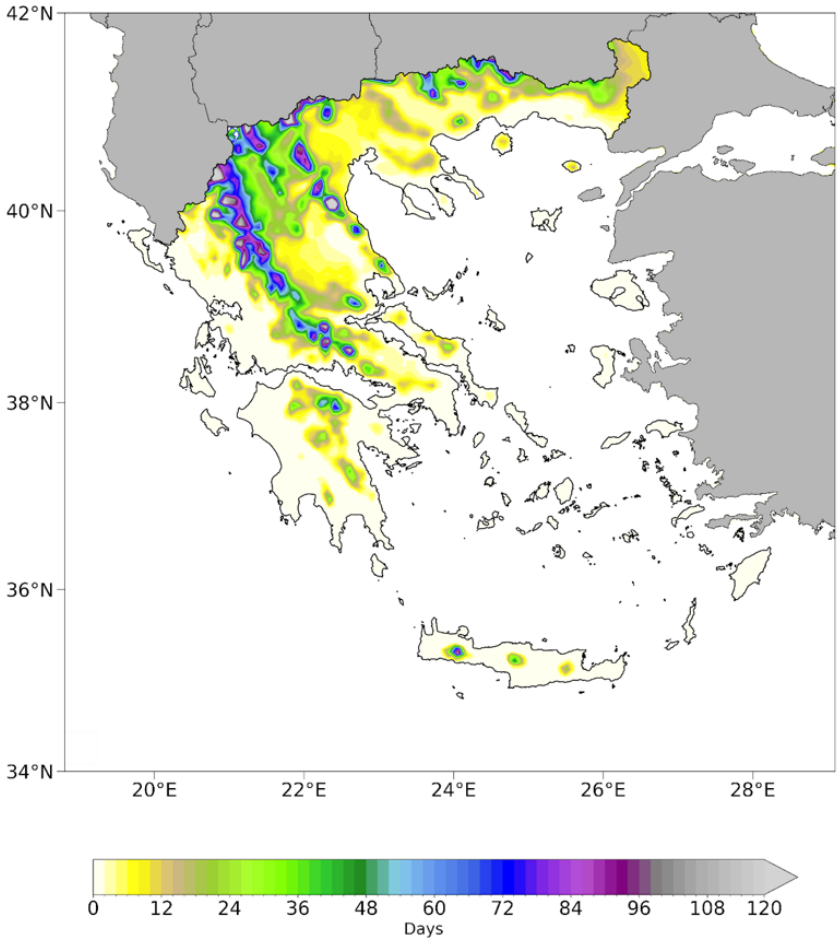


Figure 2. Average number of snow cover days per calendar year for the period 1991–2020.

When analyzing the number of snow cover days independently for the three decades between 1991 and 2020, it became evident that, during the first decade (1991–2000), the number of snow cover days in most mountainous areas of North and Central Greece was higher than the 30-year average (Figure 3a,d). Then, in the following decade (2001–2010), the largest part of Continental Greece had more snow cover days than the 1991–2020 period (Figure 3b,e). However, in the last decade analyzed (2011–2020), snow cover was dramatically reduced in duration, mainly in mountainous areas (Figure 3c,f). This reduction was particularly significant, with some regions experiencing a decrease of up to 25 days compared to the climatological average. It should be noted that the area of Northwestern Greece where the most pronounced decrease in snow cover days was found (Figure 3f) over the last decade considered (2011–2020) coincided with the area where 2 m temperature showing the largest increase during 1991–2020, with a cumulative increase over 30 years of more than 2 C.

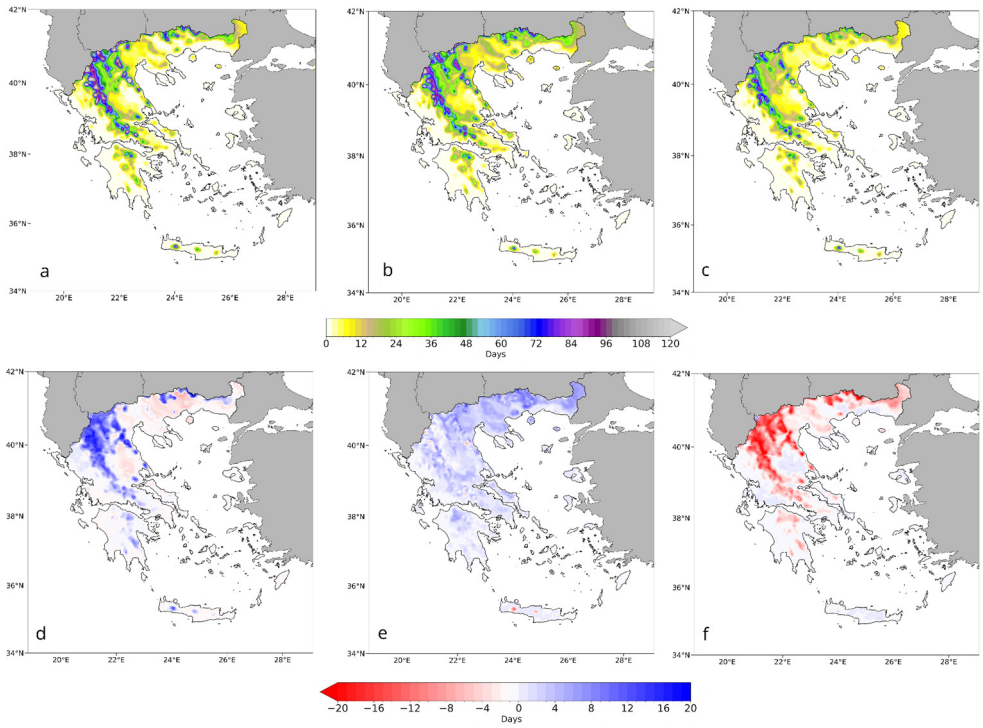


Figure 3. Average number of snow cover days per calendar year (**upper row**) and deviation in snow cover days based on 1991–2020 climatology (**lower row**) for the decades 1991–2000 (**a**,**d**), 2001–2010 (**b**,**e**), and 2011–2020 (**c**,**f**).

Figure 4 shows the yearly deviation in the number of snow cover from 1991 to 2020, depicting the difference in the number of days with snow cover, relative to the climatological baseline for the same period (1991–2020). The CERRA-Land data revealed a significant interannual variability in snow cover across Greece. Early in the record (1991–1996), especially in 1991 and 1993, the days of snow cover were much more numerous compared to the climatology (up to 35 days more). The late 1990s (1997–1999) shifted to mostly neutral or slightly negative deviations, suggesting that snow cover was closer to or slightly below the climatological average. The 2000s were marked by oscillations between positive and negative deviations. The years 2001, 2005, and 2012 stood out, indicating significantly more snow days than the average. In contrast, 2007 and 2008 exhibited strong negative deviations.

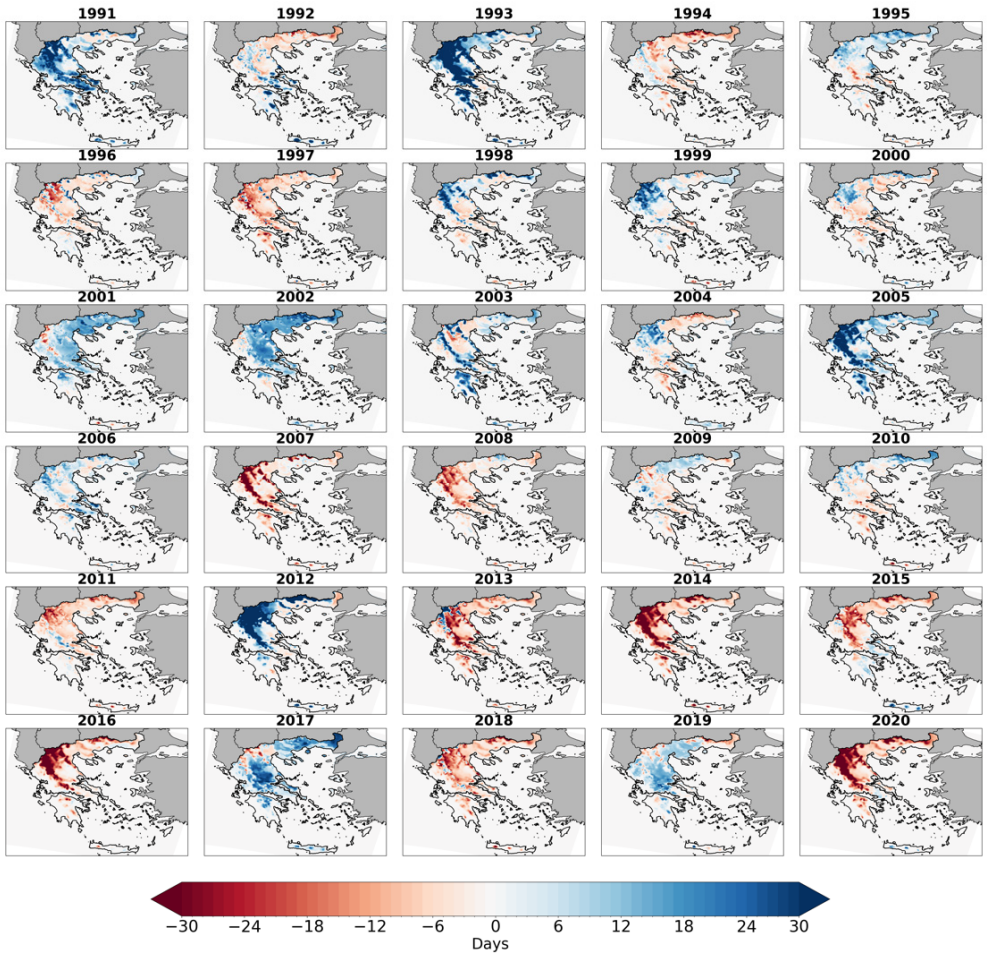


Figure 4. Yearly deviation in snow cover days based on 1991–2020 climatology.

After 2010, the pattern shifted with a notable increase in the years showing negative deviations. For the period starting in 2010, 7 out of the 10 years taken into consideration showed pronounced and widespread negative deviations across nearly the entire region, underscoring a significant and extended reduction in snow cover duration. From 2013 to 2019, negative deviations were predominant, indicating a consistent trend of fewer snow cover days. The years 2014, 2016, and 2020 had the most areas with the highest negative deviations, reflecting a major reduction in snow cover days.

3.2. Trends in Snow Cover Days

The MK test results revealed a significant negative trend in snow cover days in most mountainous areas in Greece throughout the study period (Figure 5a). Areas with a strong negative trend, primarily in Northern and Central Greece, showed the most pronounced decreases in snow cover days, with reductions of up to −1.5 days per year. This significant negative trend suggested substantial decreases in snowfall or changes in snow persistence over time. Limited areas in Northern Greece showed trends toward increased snow days (evidenced by the light blue shades in Figure 5a), but these were minimal and isolated, lacking statistical significance. While there might have been year-to-year variability, the general trend for the snow-prone mountainous areas in this region leaned heavily toward a reduction in snow cover. Focusing on the areas featuring elevations higher than 500 m, it was found that 20% of these areas experienced a decrease in the number of snow-cover days, with values of 6.6% considered statistically significant. These areas were primarily located in Northwestern Greece. On the other hand, a very small percentage of regions

showed a positive trend, with less than 1% of the area exhibiting a statistically significant increase in snow cover days.

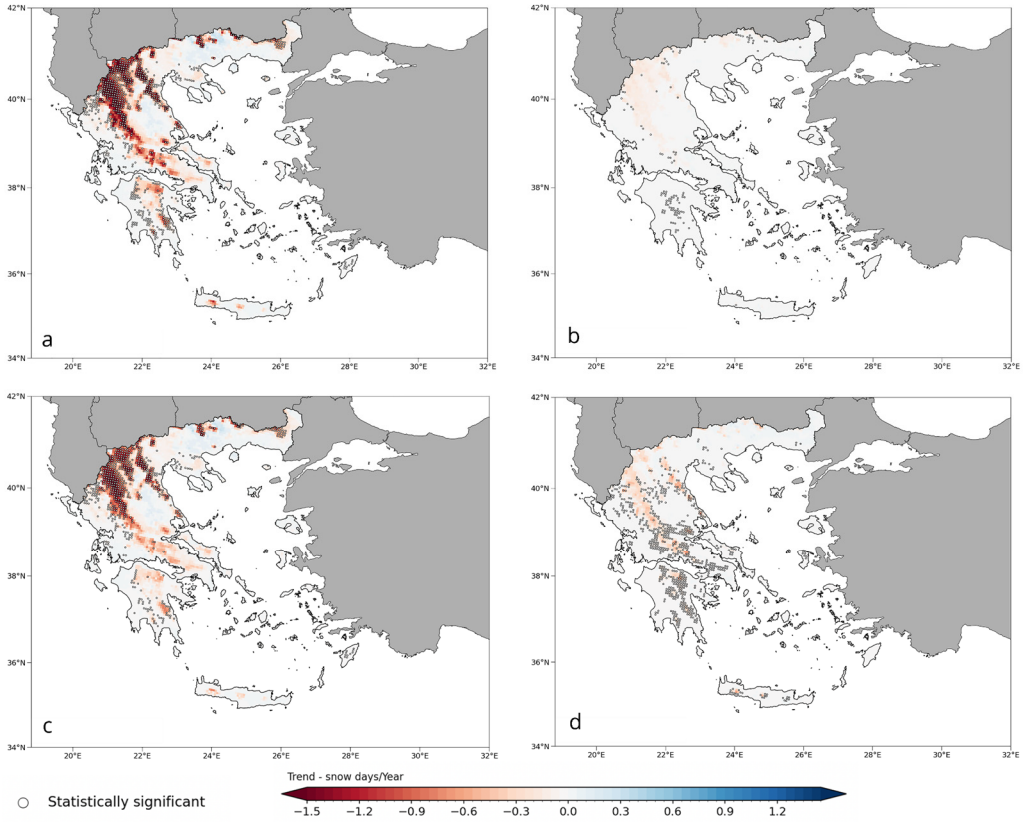


Figure 5. Trend in snow cover days over Greece in the period 1991–2020: September to May (**a**), autumn (**b**), winter (**c**), and spring (**d**). The white dots indicate regions where the observed trend in snow cover days is statistically significant ($p < 0.05$) based on the MK test.

An analysis of snow cover day trends in autumn (Figure 5b) revealed that the overall trend in Greece was notably subdued compared to the broader September-to-May period (Figure 5a). According to the analysis, a minor or negligible trend in snow cover days was found in autumn across most of the country. This was not the case for winter months (Figure 5c), when a substantial negative trend in snow cover days was evident throughout much of Northern and Central Greece, particularly in mountainous and higher-elevation regions. This indicated a clear and significant reduction in snow cover days during the winter months, up to −1.5 days per year. The consistency and concentration of these significant trends highlighted a substantial and persistent decrease in winter snow cover over the 30-year period. In spring, a decrease in snow cover days was also evident, especially in Central Greece. Compared to the autumn and winter maps, the spring trend showed a similar negative pattern, but with more statistically significant areas, indicating that the reduction in snow cover days during spring was more widespread and pronounced.

3.3. Snow Depth Climatology

The spatial distribution of snow depth in Greece revealed significant geographical variability, primarily influenced by elevation and latitude. The snow depth values in this study might have been lower than the actual ones, mostly due to the lower elevation of the modeled ground and the spatial resolution of the CERRA-Land dataset. However, the spatial and temporal distribution of snow depth in the analyzed dataset was considered reliable. Indeed, the greatest snow depths were observed in the mountainous regions of Northern and Central Greece, particularly along the Pindus Mountain range and the

country's northern borders with Albania and North Macedonia (Figure 6). These areas consistently exhibited snow depths exceeding 30 cm, with localized peaks reaching over 42 cm, reflecting the impact of orographic effects and cooler temperatures at higher altitudes. In contrast, snow depths diminished significantly in lower-altitude and southern regions, including the Peloponnese and Crete, where the average values remained below 12 cm. Coastal areas and islands experienced minimal or negligible snow accumulation due to milder temperatures and limited snowfall.

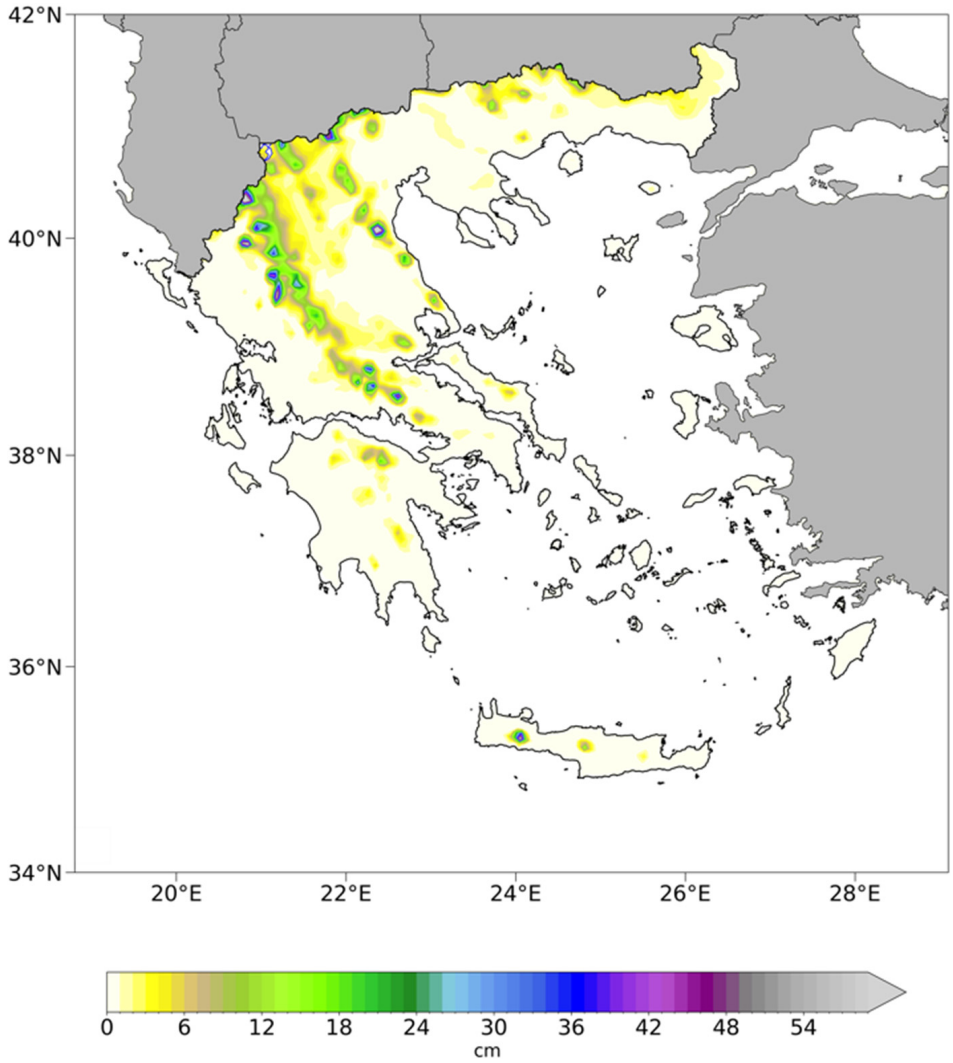


Figure 6. Average snow depth (cm) between September and May for the period 1991–2020.

Looking into the chosen consecutive decades, it was found that, during the first decade (1991–2000), significant snow depths were concentrated in the northern and mountainous areas of Central Greece, with values reaching over 30 cm in some regions. During the 2001–2010 period, the spatial extent of high snow depth was reduced, while, during the last decade considered (2011–2020), snow depth decreased further, with only limited areas in Northern Greece maintaining a moderate snow depth, highlighting a consistent trend of snow depth reduction over time.

Inspection of the deviation in the snow depth from the 1991–2020 baseline (Figure 7d–f) further supported the findings of the observed trends. During 1991–2000, deviations were minor, with slight positive anomalies in some northern regions, indicating snow depth conditions close to the baseline. However, the 2001–2010 period exhibited widespread positive deviations (Figure 7e), especially in Central and Northern Greece, denoting an

increase in the snow depth. The negative trend was most pronounced in 2011–2020, where large negative deviations dominated, particularly in central and southern areas, with reductions exceeding 12 cm in some regions (Figure 7f).

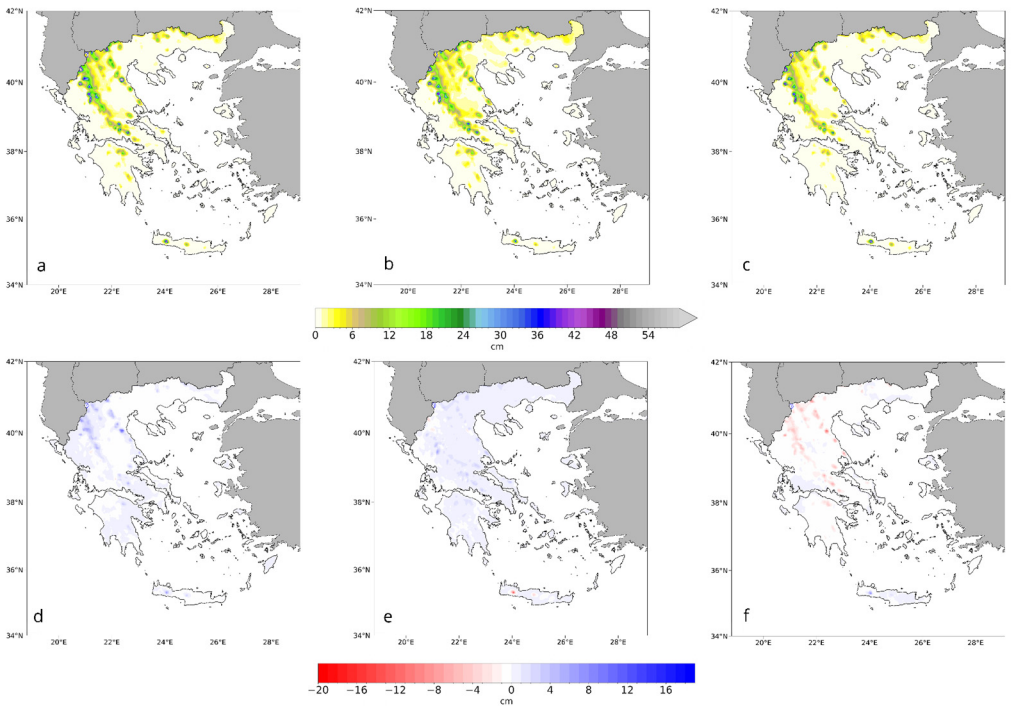


Figure 7. Average snow depth per calendar year (**upper row**) and deviation in snow depth based on 1991–2020 climatology (**lower row**) for the decades 1991–2000 (**a**,**d**), 2001–2010 (**b**,**e**), and 2011–2020 (**c**,**f**).

A substantial interannual variability in snow depth across Greece is evident in Figure 8. The early 1990s exhibited a mix of positive and negative deviations. For instance, 1991 and 1993 showed positive deviations, indicating years with snow depths above the climatological average. In contrast, 1992, 1996, and 1997 displayed negative deviations, suggesting below-average snow depths. The 2000s showed pronounced shifts: years like 2002, 2003, and 2005 featured positive deviations with significant snow depths, whereas 2007 and 2008 showed sharp negative deviations, indicating substantial reductions. From 2010 onwards, the trend began to lean more consistently toward negative deviations. The most striking negative deviations were observed in 2014, 2015, 2016, and 2020, suggesting a notable decrease in snow cover depth. Positive deviations became rarer in the more recent years considered, with only a few isolated years like 2012, 2017, and 2019 showing increases in snow cover depth.

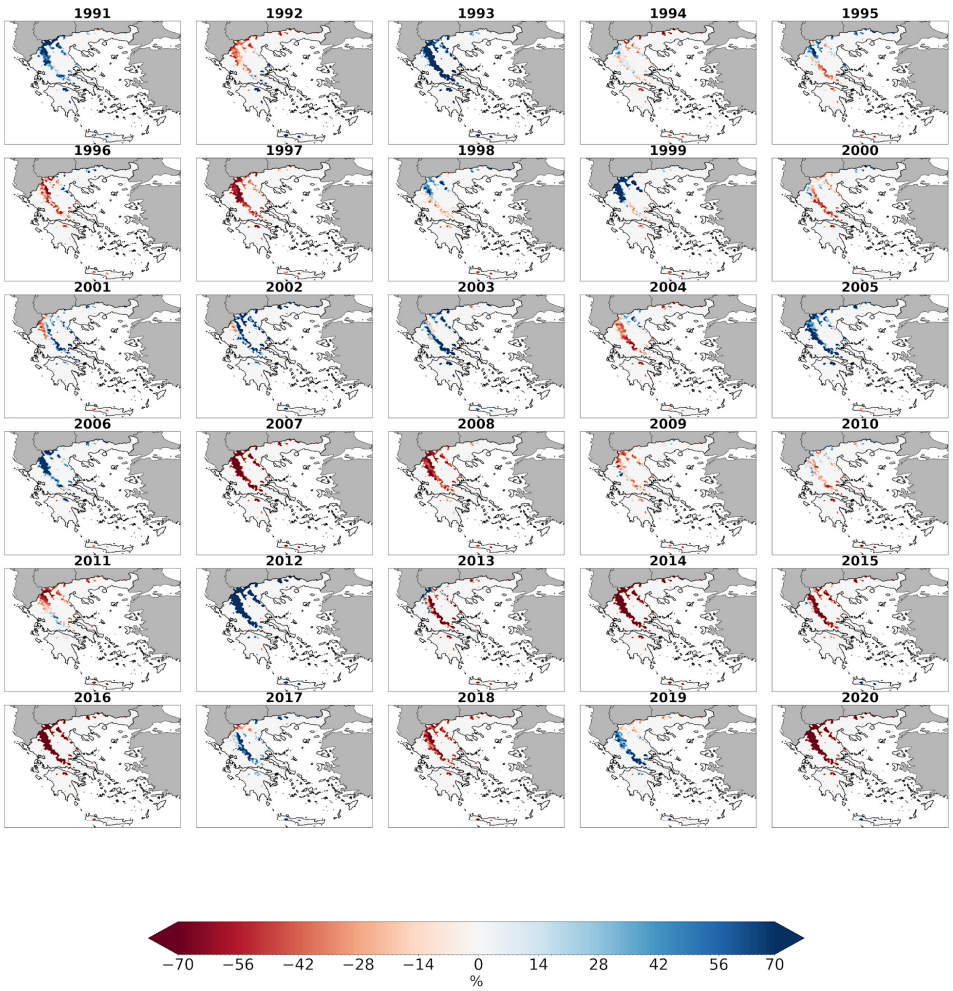


Figure 8. Yearly deviation in snow cover depth (in percentage) for Greece from 1991 to 2020, covering the period between September and May.

3.4. Trends in Snow Depth

A clear and consistent decrease in snow depth over time is evident in Figure 9, with the decline becoming more spatially widespread and statistically significant during the last two decades of the analyzed period. During the first decade (1991–2000), negative trends dominated in Northern and Central Greece, but the extent of statistically significant changes was relatively limited. Some areas, particularly in Northern Greece, showed localized positive trends, albeit minimal and not widespread. The second decade (2001–2010) showed a sharper and more extensive decrease in snow depth (Figure 9b), especially in the northern and mountainous regions of Central Greece. The negative trends became larger, with extended areas experiencing statistically significant reductions in snow depth. This indicated that, during this decade, an acceleration in snow loss occurred compared to the previous one. The last and most recent decade considered (2011–2020) demonstrated the most pronounced decrease in snow depth. The areas with statistically significant negative trends expanded further, covering much of Northern Greece and spreading into southern regions as well. There was little evidence of positive trends in this period, mostly in the mountains of Crete, but with no statistical significance. Finally, when considering the whole 30-year period (Figure 9d), only negative trends were evident throughout Greece, and they were statistically significant in Northwest Greece, the area with the most pronounced warming in the period of 1991–2020.

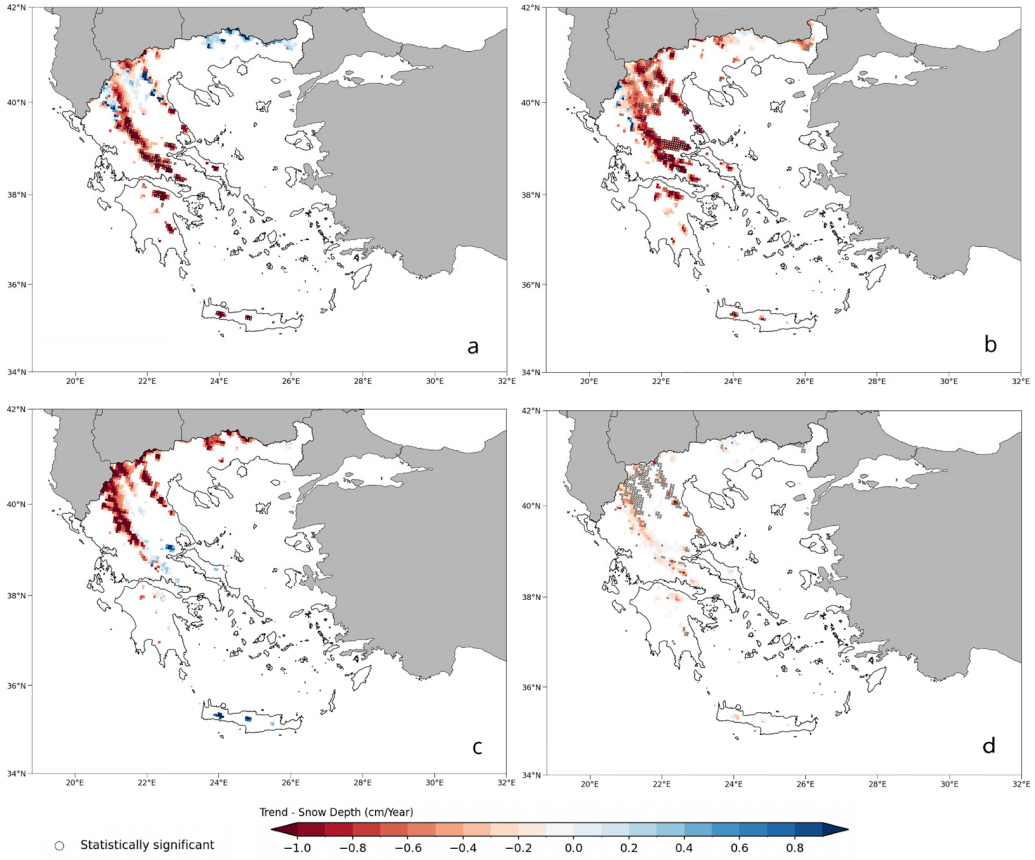


Figure 9. Trend in snow depth per calendar year in Greece during 1991–2000 (**a**), 2001–2010 (**b**), 2011–2020 (**c**), and the whole period from 1991 to 2020 (**d**). The white dots indicate regions where the observed trend in snow depth is statistically significant ($p < 0.05$) based on the MK test.

3.5. Evolution of Snow Depth in Greek Ski Centers

Snow plays a crucial role in the winter economy, especially in regions that rely on tourism and winter sports. Ski resorts depend heavily on consistent snowfall to attract tourists. This is the reason why, in this section, we focused on the analysis of snow depth specifically over major ski centers in Greece. Indeed, Figure 10 provides an insightful comparison of average snow depth evolution across nine ski centers. We focused on the wet period (September through May), and the three consecutive decades of 1991–2000, 2001–2010, and 2011–2020 were also analyzed separately. It is clear that snow depths have decreased over the years, with the most recent decade (2011–2020) consistently displaying lower snow accumulation compared to the earlier decades. This trend highlights a significant reduction in snow accumulation over time, implying that the conditions for sustained snow cover in Greek ski centers have weakened.

One of the most evident patterns is the decrease and seasonal shift in peak snow depths. In the decade of 1991–2000, snow depth often reached higher maximum values that persisted longer into the season, extending into late winter and early spring. In contrast, the 2011–2020 decade showed lower peaks, with decreased maximum snow depths and an earlier melt, indicating a shorter snow season. This pattern was particularly evident in ski centers like Kaimaktsalan (Figure 10a), 3–5 Pigadia (Figure 10b), Seli (Figure 10c), and the northern part of Greece, where snow depths have notably decreased in the most recent decade compared to the early 1990s. During the first two decades considered, the earlier peaks were sustained and supported a longer duration of snow cover, but the recent decade reflected not only a drop in these peaks but also a quicker decline in snow depth as the season progressed.

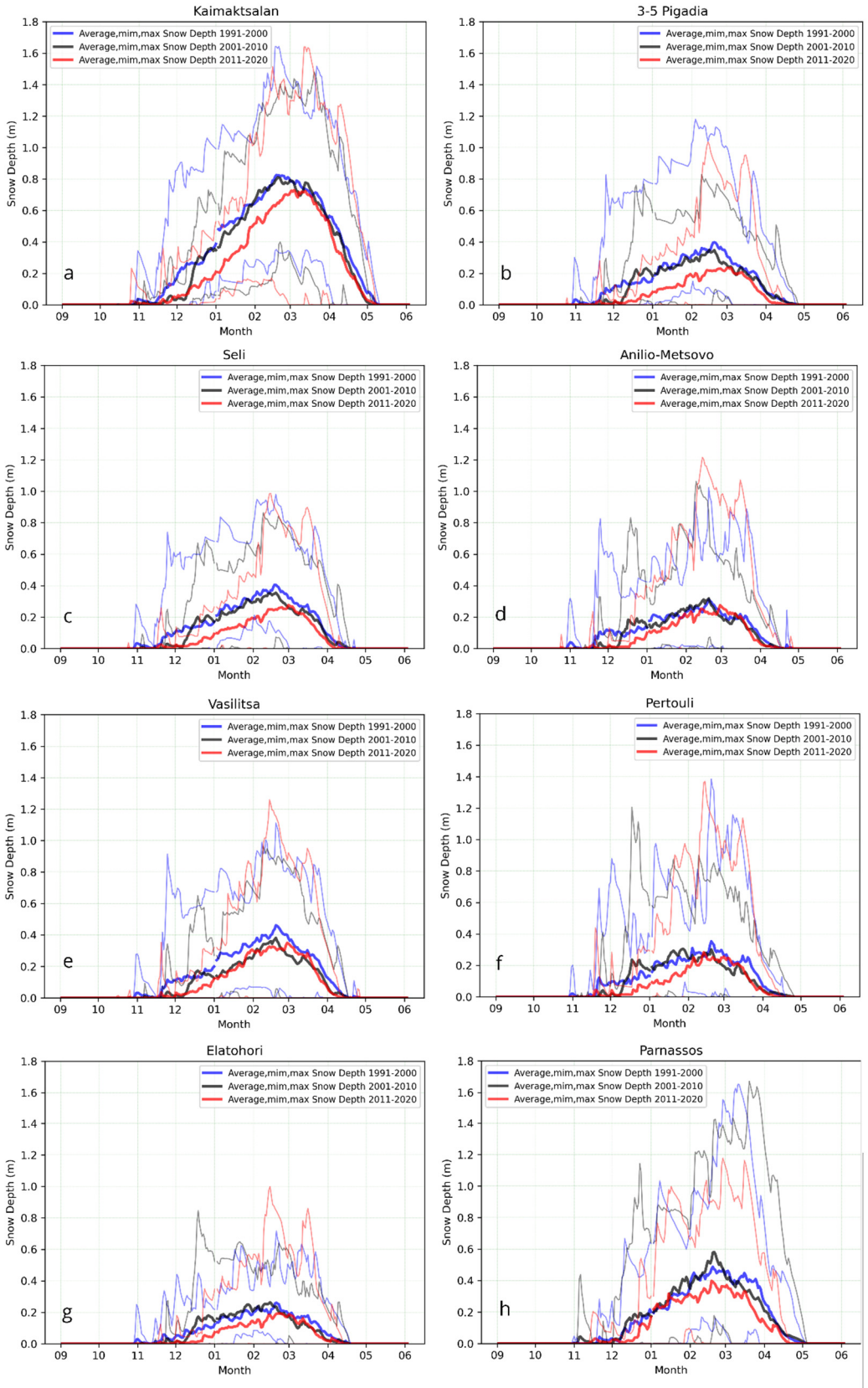


Figure 10. Average snow depth evolution over three decades: 1991–2000 (blue line), 2001–2010 (black line), and 2011–2020 (red line) at nine Greek ski centers: (**a**) Kaimaktsalan, (**b**) 3-5 Pigadia, (**c**) Seli, (**d**) Anilio- Metsovo, (**e**) Vasilitsa, (**f**) Pertouli, (**g**) Elatochori, (**h**) Parnassos. The *x*-axis represents months (September to June), and the *y*-axis shows snow depth in meters.

Specific observations at centers such as 3–5 Pigadia and Seli revealed consistent decreases in the snow depth during the consecutive decades considered, with the first decade showing stable and substantial snow cover, while the latest decade indicated less snow accumulation, peaking at lower values and later in the season, with a snow season which started later and ended earlier. This trend aligned with the snow depth evolution across most of the ski centers, underscoring the overall pattern of reduced snow cover. Pertouli (Figure 10f) and Vasilitsa (Figure 10e) demonstrated a similar trend, with marked reductions in the average snow depth, particularly after February, suggesting that the duration of the snow season shortened over the decades. This pattern was more pronounced in Vasilitsa, where, during the most recent decade considered, the snow depth in the autumn was minimal, while it decreased fast and much earlier, in the early spring. Similar findings were discussed based on data from a weather station in the broader Pertouli area, where decreasing trends in snow cover found during the autumn were statistically significant [29].

Ski centers in Parnassos (Figure 10h), Anilio (Figure 10d), and Elatohori (Figure 10g) also reflected the trend of declining snow depths. The earlier decades, especially 1991–2000, showed more pronounced snow depth peaks that were sustained for a longer period, whereas the 2011–2020 period featured lower peaks and an accelerated decrease, signifying a shorter overall snow season. Comparing the three decades, the data revealed that the 1991–2000 period was characterized by higher and more stable snow depths, indicative of consistent and prolonged snow seasons. The 2001–2010 decade, while still showing significant accumulation, hinted at some variability and initial signs of decline in snow cover and duration. The average 2011–2020 period stood out as markedly lower in terms of snow depth, whereas lower peaks of maximum values confirmed that the snow cover in Greece's ski centers became increasingly sparse and less reliable over the years.

In addition, the number of days with snow cover was calculated and provided further insights into the changes that occurred in eight Greek ski centers over the last three decades. Table 1 summarizes the average number of days with snow cover between September and May for each ski resort during the three periods (1991–2000, 2001–2010, and 2011–2020), alongside the percentage deviation observed in the most recent decade (2011–2020) compared to the earliest one (1991–2000). The data indicate an important decrease in snow days across all ski resorts. Ski resorts located at lower altitudes, such as Pertouli, 3–5 Pigadia, Elatohori, and Seli, demonstrated significant decreases in snow cover. During the second decade considered (2001–2010), a reduction in snow cover days had already become apparent, with a progressive decline, culminating in percentage decreases of up to 36% during the most recent decade (2011–2020) compared to the first decade (1991–2000). On the other hand, ski resorts at higher altitudes (>1900 m), such as Kaimaktsalan and Parnassos, maintained more consistent snow cover during the first decade considered (1991–2000). By the second decade in this study (2001–2010), a gradual decline was observed, which continued into the 2011–2020 period, resulting in comparatively smaller decreases of around 20%. These trends highlight the disproportionate impact of decreasing snow cover at lower-altitude ski resorts, while also underscoring broader, long-term effects across all elevations.

Table 1. Average number of days with snow cover per calendar year between 1991 and 2020 for each decade separately, and associated deviations between the latest and earliest decades, for eight ski resorts in Greece. The elevation (m) corresponds to the base of each ski resort.

Ski Resort	Elevation (m)	Avg Snow Days (1991–2000)	Avg Snow Days (2001–2010)	Avg Snow Days (2011–2020)	% Deviation (2011–2020) and (1991–2000)
Kaimaktsalan	2247	152	143	134	−18
3–5 Pigadia	1707	112	102	82	−30
Seli	1674	109	95	78	−31
Anilio	1729	98	92	77	−21
Vasilitsa	1874	111	94	86	−25
Pertouli	1255	100	91	73	−27
Elatochori	1666	101	88	65	−36
Parnassos	1915	110	99	91	−19

4. Discussion

The analysis of snow cover and snow depth trends in Greece over the past three decades, using the CERRA-Land reanalysis dataset, provides a comprehensive understanding of the impacts of climate change on the region's snow conditions. The data indicate a significant decrease in both the extent and duration of snow cover, particularly in the last decade considered (2011–2020), emphasizing the vulnerability of Greece's mountainous regions to warming temperatures and shifting precipitation patterns. After 2010, a clear shift emerged, with a marked rise in the frequency of years exhibiting negative deviations. Notably, 7 out of the past 10 years displayed significant and widespread reductions in snow cover duration across nearly the entire region. This decline was particularly acute in the mountainous regions of Northern and Central Greece, where snow cover days decreased by as much as 25 days compared to climatological averages in some areas. These findings align with global studies that highlight the sensitivity of snow cover to temperature variations and its substantial decline due to warming climates [4,5,8]. This decrease was more evident in the comparative analysis between the ski centers, which showed marked decreases in snow depth and a noticeable shortening of the snow season over time.

The spatial analysis revealed that the northern and central mountainous areas of Greece, particularly along the Pindus and Rhodopi mountain ranges, historically experienced the largest number of snow cover days and the deepest snow accumulations. However, these regions have since shown significant negative trends, with reductions in snow cover days of up to −1.5 days per year. The seasonal breakdown of these trends highlights that winter months experience the most significant decline, with the most substantial decreases observed in the peak winter season. Spring trends similarly reflect a pronounced reduction in snow cover days, indicating an earlier melt and a truncated snow season. This pattern is consistent with findings noting significant snow season shortening in Southern and Eastern Europe [14,30,31]. The earlier onset of snowmelt has profound implications for water resources, ecosystems, and human activities that rely on consistent snow cover [3].

Yearly deviations in snow depth further underline this decreasing pattern. While the early 1990s displayed variability with both positive and negative deviations from the 30-year average, the later years, particularly after 2010, showed a persistent shift toward negative deviations. The most pronounced decreases in snow depth were observed in 2014, 2015, 2016, and 2020, suggesting that the impact of warming temperatures has accelerated in recent years, resulting in less consistent and shorter-lasting snow cover.

Positive deviations have become rare, and even in years with above-average precipitation [32], the increases are not substantial enough to counteract the longer-term downward trend. Similar trends have been documented across European mountain ranges, where diminishing snow accumulation is attributed to increased temperatures and changes in precipitation patterns [14,33].

The decline in snow conditions is particularly concerning for the ski industry, a vital economic sector in Greece's mountainous regions. The analysis of snow depth evolution in nine major ski centers between 1991 and 2020 shows a clear pattern of decreased snow depth in recent years. In the decade of 1991–2000, snow depth at these ski centers reached higher maxima that persisted through late winter and into early spring, providing longer and more reliable ski seasons. The following decade (2001–2010) maintained significant snow accumulation, though variability began to emerge, indicating early signs of declining snow reliability. By the most recent decade (2011–2020), the data showed considerably lower peaks in snow depth and an earlier decline, signaling a significant shortening of the snow season and posing substantial challenges for ski tourism. These observations are supported by findings indicating that rising temperatures and reduced natural snowfall could significantly shorten ski seasons and affect winter tourism across Europe [10,30,34,35].

The primary limitation of this study lies in the reliability of the reanalysis data (CERRA-Land), which, although valuable for large-scale analyses, may lack the precision of ground-based measurements in capturing localized snow conditions, especially in regions with complex terrain [23]. The use of a single reanalysis product also raises questions about potential biases inherent in the model's representation of snow processes, but the lack of a ground-based observational network for snow conditions in Greece inhibits any relevant study based on in situ measurements.

5. Conclusions

In conclusion, this study underscores the pressing need for region-specific adaptation strategies to address the challenges posed by declining snow cover and depth in Greece. The reduction in snow days and depth aligns with the broader trends observed across Europe and highlights the vulnerability of Greece's mountainous regions to climate change. Adaptation measures, such as the development of artificial snowmaking technology and diversified tourism strategies, could help mitigate some of the impacts. However, without global and regional efforts to curb warming trends, the long-term sustainability of winter tourism and snow-dependent ecosystems in Greece remains uncertain [14].

Future work should aim to incorporate a more robust network of in situ snow measurements across Greece, enabling the cross-validation of reanalysis and satellite data. Expanding the analysis to include snow water equivalent (SWE) data could provide a more comprehensive understanding of the impact on water resources. Studies could also examine the role of extreme weather events, such as sudden warm spells and heavy precipitation, in altering snow conditions and their implications for the persistence of snow cover. Incorporating climate models that project future scenarios based on varying emissions pathways (e.g., RCP 4.5 and RCP 8.5) would aid in assessing long-term changes and potential adaptation measures for winter tourism and water resource management.

Finally, it would be beneficial to extend the analysis beyond ski centers to assess the impacts on other snow-dependent sectors and ecosystems, such as agriculture and forestry, and evaluate socioeconomic repercussions for local communities reliant on snow for tourism and other seasonal activities. Regional collaborative studies across Southeastern Europe could also provide comparative insights, addressing the research gaps highlighted by the IPCC (2022) for Eastern European snow and climate impact studies.

Author Contributions: Conceptualization, K.L., V.K. and S.D.; methodology, I.M., G.K. and S.D.; software, I.M., G.K. and S.D.; validation, I.M., G.K., S.D. and K.L.; formal analysis, I.M. and S.D.; investigation, I.M., G.K. and S.D.; resources, I.M., G.K. and S.D. data curation, I.M. and G.K; writing—original draft preparation, I.M. and S.D.; writing—review and editing, I.M., S.D., K.L. and V.K.; visualization, I.M., S.D. and G.K.; supervision, S.D., K.L. and V.K.; project administration, K.L. and V.K.; funding acquisition, K.L. and V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research work was funded by project SNOWCLIM (grant agreement: G-2308-66609, European Climate Foundation).

Data Availability Statement: The original data presented in the study are openly available in Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.a7f3cd0b. Calculated data presented in this article will be made available by the authors on request.

Acknowledgments: The authors gratefully acknowledge the nine Greek ski centers and Copernicus Climate Change Service (C3S) for providing access to the Copernicus European Regional RE-Analysis Land (CERRA-Land) dataset: https://climate.copernicus.eu/copernicus-regional-reanalysis-europe-cer.ra (accessed on 10 October 2024).

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

References

1. Sturm, M.; Goldstein, M.A.; Parr, C. Water and life from snow: A trillion dollar science question. *Water Resour. Res.* **2017**, *53*, 3534–3544. [CrossRef]
2. Pulliainen, J.; Luojus, K.; Derksen, C.; Mudryk, L.; Lemmetyinen, J.; Salminen, M.; Ikonen, J.; Takala, M.; Cohen, J.; Smolander, T.; et al. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. *Nature* **2020**, *581*, 294–298. [CrossRef]
3. Barnett, T.P.; Adam, J.C.; Lettenmaier, D.P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **2005**, *438*, 303–309. [CrossRef]
4. Henderson, G.R.; Leathers, A.M.; Robinson, D.A. Northern Hemisphere Snow Cover Variability and Change. *J. Clim.* **2018**, *31*, 6517–6531.
5. Notarnicola, C. Overall negative trends for snow cover extent and duration in global mountain regions over 1982–2020. *Sci. Rep.* **2022**, *12*, 13731. [CrossRef]
6. Brown, R.D. Northern Hemisphere Snow Cover Variability and Change, 1915–1997. *J. Clim.* **2020**, *13*, 2339–2355. [CrossRef]
7. Beniston, M. Variations of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in large-scale climatic forcings. *Clim. Change* **1997**, *36*, 281–300. [CrossRef]
8. Flanner, M.G.; Shell, K.M.; Barlage, M.; Perovich, D.K.; Tschudi, M.A. Radiative Forcing and Albedo Feedback from the Northern Hemisphere Cryosphere between 1979 and 2008. *Nat. Geosci.* **2011**, *4*, 151–155. [CrossRef]
9. Pulliainen, J.; Aaltonen, A.K.; Rautiainen, M.; Hallikainen, M.T.; Salberg, R. The Role of Snow in the Global Carbon Cycle. *Nat. Clim. Change* **2017**, *7*, 833–839.
10. Steiger, R.; Scott, D.; Abegg, B.; Pons, M.; Aall, C. A critical review of climate change risk for ski tourism. *Curr. Issues Tour.* **2017**, *22*, 1343–1379. [CrossRef]
11. Ogrin, M.; Ogrin, D.; Rodman, N.; Močnik, M.; Vengar, R.; Smolej, A.; Bunčič, G. Climate change and the future of winter tourism in Slovenia. *Hrvat. Geogr. Glas.* **2011**, *73*, 215–228. [CrossRef]
12. Masloumidis, I.; Dafis, S.; Kyros, G.; Lagouvardos, K. Snow Depth Trends of European Ski Resorts. *Environ. Sci. Proc.* **2023**, *26*, 16. [CrossRef]
13. Demiroglu, O.C.; Kučerová, J.; Ozcelebi, O. Snow reliability and climate elasticity: Case of a Slovak ski resort. *Tour. Rev.* **2015**, *70*, 1–12. [CrossRef]
14. Intergovernmental Panel on Climate Change (IPCC). *Sixth Assessment Report: Impacts, Adaptation and Vulnerability*; IPCC: Geneva, Switzerland, 2022; Available online: https://www.ipcc.ch/report/ar6/wg2 (accessed on 10 October 2024).
15. Beniston, M.; Farinotti, D.; Stoffel, M.; Andreassen, L.M.; Coppola, E.; Eckert, N.; Fantini, A.; Giacona, F.; Hauck, C.; Huss, M.; et al. The European mountain cryosphere: A review of its current state, trends, and future challenges. *Cryosphere* **2018**, *12*, 759–794. [CrossRef]
16. Morin, S.; Samacoïts, R.; François, H.; Carmagnola, C.M.; Abegg, B.; Demiroglu, O.C.; Pons, M.; Soubeyroux, J.M.; Lafaysse, M.; Franklin, S.; et al. Pan-European meteorological and snow indicators of climate change impact on ski tourism. *Clim. Serv.* **2021**, *22*, 100215. [CrossRef]

17. Tsilogianni, D.; Cartalis, C.; Philippopoulos, K. Climate Change Impact Assessment on Ski Tourism in Greece: Case Study of the Parnassos Ski Resort. *Climate* **2023**, *11*, 140. [CrossRef]
18. Essential Climate Variables. Available online: https://gcos.wmo.int/en/essential-climate-variables/table (accessed on 5 October 2024).
19. de Rosnay, P.; Balsamo, G.; Albergel, C.; Muñoz-Sabater, J.; Isaksen, L. Initialisation of land surface variables for numerical weather prediction. *Surv. Geophys.* **2014**, *35*, 607–621. [CrossRef]
20. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger Climate Classification Updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
21. Feidas, H.; Noulopoulou, C.; Makrogiannis, T.; Bora-Senta, E. Trend Analysis of Precipitation Time Series in Greece and Their Relationship with Circulation Using Surface and Satellite Data: 1955–2001. *Theor. Appl. Climatol.* **2007**, *87*, 155–177. [CrossRef]
22. Tziallas, H. Mountainous Landscapes and Climate Variability in Greece: Impacts on Tourism and Development. *Reg. Environ. Change* **2015**, *15*, 743–754.
23. Verrelle, A.; Glinton, M.; Bazile, E.; Le Moigne, P.; Randriamampianina, R.; Ridal, M.; Berggren, L.; Undén, P.; Schimanke, S.; Mladek, R.; et al. CERRA-Land Sub-Daily Regional Reanalysis Data for Europe from 1984 to Present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). 2022. Available online: https://cds.climate.copernicus.eu/datasets/reanalysis-cerra-land?tab=overview (accessed on 27 November 2024).
24. U.S. National Ice Center. *IMS Daily Northern Hemisphere Snow and Ice Analysis at 1 km, 4 km, and 24 km Resolutions*; (G02156, Version 1); National Snow and Ice Data Center: Boulder, CO, USA, 2008. [CrossRef]
25. Mazari, N.; Tekeli, A.E.; Xie, H.; Sharif, H.O.; El Hassan, A.A. Assessment of ice mapping system and moderate resolution imaging spectroradiometer snow cover maps over Colorado Plateau. *J. Appl. Remote Sens.* **2013**, *7*, 073540. [CrossRef]
26. Sönmez, I.; Tekeli, A.E.; Erdi, E. Snow cover trend analysis using Interactive Multisensor Snow and Ice Mapping System data over Turkey. *Int. J. Climatol.* **2014**, *34*, 2349–2361. [CrossRef]
27. Monteiro, D.; Morin, S. Multi-decadal past winter temperature, precipitation and snow cover information over the European Alps using multiple datasets. *EGUsphere* **2023**, *17*, 3617–3660. [CrossRef]
28. Skimap. Available online: https://skimap.org/ (accessed on 14 May 2023).
29. Stefanidis, S.; Stathis, D.; Dafis, S. The characteristics of snowfall in the mountainous areas of Trikala region. In Proceedings of the 19th Forestry Conference, Litochoro, Greece, 5 October 2019.
30. Amihăesei, V.-A.; Micu, D.-M.; Cheval, S.; Dumitrescu, A.; Sfîcă, L.; Bîrsan, M.-V. Changes in snow cover climatology and its elevation dependency over Romania (1961–2020). *J. Hydrol. Reg. Stud.* **2024**, *51*, 101637. [CrossRef]
31. Bendorz, E.; Kossowski, T. Long-term changes in snow cover depth in eastern Europe. *Clim. Res.* **2024**, *27*, 231–236. [CrossRef]
32. Lagouvardos, K.; Dafis, S.; Kotroni, V.; Kyros, G.; Giannaros, C. Exploring Recent (1991–2020) Trends of Essential Climate Variables in Greece. *Atmosphere* **2024**, *15*, 1104. [CrossRef]
33. Morán-Tejeda, E.; López-Moreno, J.I.; Beniston, M. The changing roles of temperature and precipitation on snowpack variability in Switzerland as a function of altitude. *Geophys. Res. Lett.* **2013**, *40*, 2131–2136. [CrossRef]
34. Bednorz, E. Snow cover in Eastern Europe in relation to temperature, precipitation and circulation. *Int. J. Climatol.* **2004**, *24*, 591–601. [CrossRef]
35. Bednorz, E. Synoptic conditions of heavy snowfalls in Europe. *Geogr. Ann. Ser. A Phys. Geogr.* **2013**, *95*, 67–78. [CrossRef]

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