atmosphere

MDPI

Article

Future Changes in Euro-Mediterranean Daytime Severe Thunderstorm Environments Based on an RCP8.5 Med-CORDEX Simulation

Abdullah Kahraman [1,2,*], Deniz Ural [3,4] and Barış Önol [5]

[1] Department of Meteorological Engineering, Faculty of Aeronautics and Astronautics, Samsun University, 55420 Samsun, Turkey
[2] School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[3] Potsdam Institute for Climate Impact Research, Climate Resilience, 14412 Potsdam, Germany; denizural86@gmail.com
[4] Alfred Wegener Institute for Polar and Marine Research, Climate Dynamics, 14473 Potsdam, Germany
[5] Department of Meteorological Engineering, Faculty of Aeronautics and Astronautics, Istanbul Technical University, 34469 Istanbul, Turkey; onolba@itu.edu.tr
* Correspondence: kahraman@meteogreen.com

Received: 19 May 2020; Accepted: 31 July 2020; Published: 4 August 2020

Abstract: Convective scale processes and, therefore, thunderstorm-related hazards cannot be simulated using regional climate models with horizontal grid spacing in the order of 10 km. However, larger-scale environmental conditions of these local high-impact phenomena can be diagnosed to assess their frequency in current and future climates. In this study, we present a daytime climatology of severe thunderstorm environments and its evolution for a wide Euro-Mediterranean domain through the 21st century, using regional climate model simulations forced by Representative Concentration Pathway (RCP) 8.5 scenario. Currently, severe convective weather is more frequently favored around Central Europe and the Mediterranean Sea. Our results suggest that with a steady progress until the end of the century, Mediterranean coasts are projected to experience a significantly higher frequency of severe thunderstorm environments, while a slight decrease over parts of continental Europe is evaluated. The increase across the Mediterranean is mostly owed to the warming sea surface, which strengthens thermodynamic conditions in the wintertime, while local factors arguably keep the shear frequency relatively higher than the entire region. On the other hand, future northward extension of the subtropical belt over Europe in the warm season reduces the number of days with severe thunderstorm environments.

Keywords: climate change; severe weather; thunderstorms; hail; tornadoes; Med-CORDEX; convective storms

1. Introduction

Thunderstorms, or with a more accurate term, deep moist convection, occur when an air parcel with sufficient moisture rises to a critical level—level of free convection—and forms an updraft due to buoyancy. The upward motion results in rapid condensation and eventually precipitation, which cools the air around due to the latent heat factor, while falling down, forming a downdraft. When the winds around a thunderstorm cell are constant with height, the downdraft occurs just over the updraft and diminishes it typically within an hour. However, environments with dramatical and steady changes of winds with height separate the updraft and downdraft, resulting in a more sustainable thunderstorm. The interaction of downdrafts with environmental winds usually triggers new cells, resulting in varying types of mesoscale convective systems. Sometimes, mostly in environments with the vertical wind shear really high (e.g., 20 ms^{-1} vectoral difference between the surface and 6 km aloft), a special type of thunderstorm, a supercell, occurs. These are rare, but reveal one of the most organized cloud structures in nature, with their rotating updrafts occasionally with astonishing views, and usually hazards such as tornadoes, very large hail, damaging winds, intense lightning, or heavy downpours.

Effects of anthropogenic climate change on the frequency and intensity of extreme weather events, especially those related with severe thunderstorms, are a hot topic of interest, exhibiting high uncertainty and regional variability [1–8]. The main conflicting aspects of severe thunderstorm environments are the increase in more favorable thermodynamic conditions and the decrease in kinematic factors (i.e., vertical wind shear) [1]. Warming and consequently higher available moisture in the atmosphere results in higher latent instability, which favors convection. However, increase in temperature is not homogeneous all over the globe, that is, higher latitudes get much warmer than the tropics, which results in weakening of thermal wind in midlatitudes and eventually jet streams, which are crucial for high vertical wind shear, to organize thunderstorms [1,4]. Although some studies indicate that more frequent severe thunderstorms are likely with combined instability and shear (e.g., in Europe [8] and in the United States [4]), there is still an uncertainty which of these two factors, if any, will compensate the other in a given region, resulting in more or less severe convection and relevant hazardous phenomena. Moreover, some studies demonstrate dissimilar arguments, such as future stratification of the troposphere via increase in warming with height [9,10]. This concept may have the consequence of less latent instability, or if valid for lower layers, an increase in convective inhibition (CIN)—eventually less frequent but stronger thunderstorms. Adding geographical and topographical features to the complexity of the problem, it is not theoretically possible to anticipate how future thunderstorm environments will differ from today's, without usage of dynamical models resolving atmospheric processes.

Despite the smaller-scale nature of convection-related phenomena, large-scale dynamics and thermodynamics provide valuable information in their analysis. The latter sets the environmental conditions necessary for the occurrence of tornadoes, hail, downbursts, and flash flood producing heavy precipitation, as well as lightning. This allows reanalysis data or coarse-scale regional climate model output to be used in building climatologies and tracking the changes in favorable environments of severe convection (e.g., a broader domain including Europe: [11], Turkey's severe thunderstorm environments: [12], Europe's current and future: [13], Europe and the United States' current and future: [1,14,15], Europe's current and future [8]).

Most of the mentioned studies are focused on the United States or Europe, or countries with a smaller geographical extent. There is no study dedicated to the Mediterranean region, although some studies do cover parts of the Mediterranean Sea. The domain choice is very important in such studies when a regional climate model is used, as the coarser resolution input from global circulation models are fed into the simulation. Inconsistencies near lateral boundaries can penetrate further into the domain for several grid points, and the resultant analysis area is usually much smaller than the domain itself. The European domains used in earlier studies usually cover the Western Mediterranean, parts of the Central Mediterranean, and exclude the Eastern Mediterranean. However, the Eastern Mediterranean and adjacent territories experience severe convective weather very frequently [16–24]. Therefore, a domain choice covering the entire sea and the surrounding territories is important to realistically assess the future changes in severe storm environments in the region.

One other caveat regarding regional climate model-based studies is the relatively smaller number of vertical levels. The vertical resolution is crucial in analyzing convective storm environments, since it determines the accuracy of thermodynamics and kinematics in a given grid cell. Also, there is a critical threshold for the number of vertical levels as it is not possible to calculate convective available potential energy (CAPE) when there are only a few vertical levels in the troposphere. This leads to usage of some other instability measures, which use a small number of levels and are relatively less representative than CAPE. The precision of vertical wind shear, which is another critical element for storm organization, is also affected by the number of vertical levels. Furthermore, as the usage of climate models is more focused on changes in temperature, precipitation, and other primary variables, it is usually hard to obtain detailed model output for instantaneous values of meteorological parameters for long terms. This is not because the models are incapable of producing such output, but due to the large volume of data to be stored. However, studies for these smaller spatial and temporal scales require higher temporal resolution, with instantaneous data. This is one of the reasons why not all model output is sufficient for doing such a study.

This study aims at finding out how daytime thunderstorm-related high-impact weather events may evolve in a possible future Euro-Mediterranean climate, under the common environmental characteristics of severe thunderstorms. We use a Mediterranean-focused and relatively extended domain, which permits calculating instantaneous thermodynamic and kinematic parameters with sufficient vertical resolution. The data and methods used are discussed in Section 2 and the results are presented in Section 3. Finally, Section 4 presents some discussions stemming from the results and concludes the paper.

2. Data and Methods

The Mediterranean Coordinated Regional Downscaling Experiment (Med-CORDEX) is a collaborative climate research framework which uses regional earth system models to investigate the past, present, and future climate of the Mediterranean region and its surroundings. Detailed information on Med-CORDEX can be obtained from the dedicated reference [25]. The model output suite used in this study is a component of the Med-CORDEX data, although keeping the specific 3D instantaneous data with enough vertical levels, such as used in our study, is not a common practice among climatologists, due to high volume and practical needs of business-as-usual climate change research. Therefore, data availability is the main limitation for a study like ours.

In this study, the regional climate simulations produced by International Centre for Theoretical Physics-Regional Climate Model (ICTP-RegCM4) [26] have been forced by Representative Concentration Pathway 8.5 Wm^{-2} (RCP8.5) scenario. The boundary conditions for the ICTP-RegCM4 were obtained from Hadley Centre Global Environment Model version 2 (HadGEM2) simulation. The simulations cover an extended area of the usual Med-CORDEX domain, even including the Caspian Sea in the east (Figure 1). The domain has 120 × 82 grid structure, with 0.44° (~50 km) horizontal grid intervals both zonally and meridionally. There are 18 vertical levels. Physical parameterizations used are: Grell cumulus scheme [27], CCM3 radiative transfer model [28], BATS surface model [29]. ICTP sea surface temperature (SST) is used in the simulations.

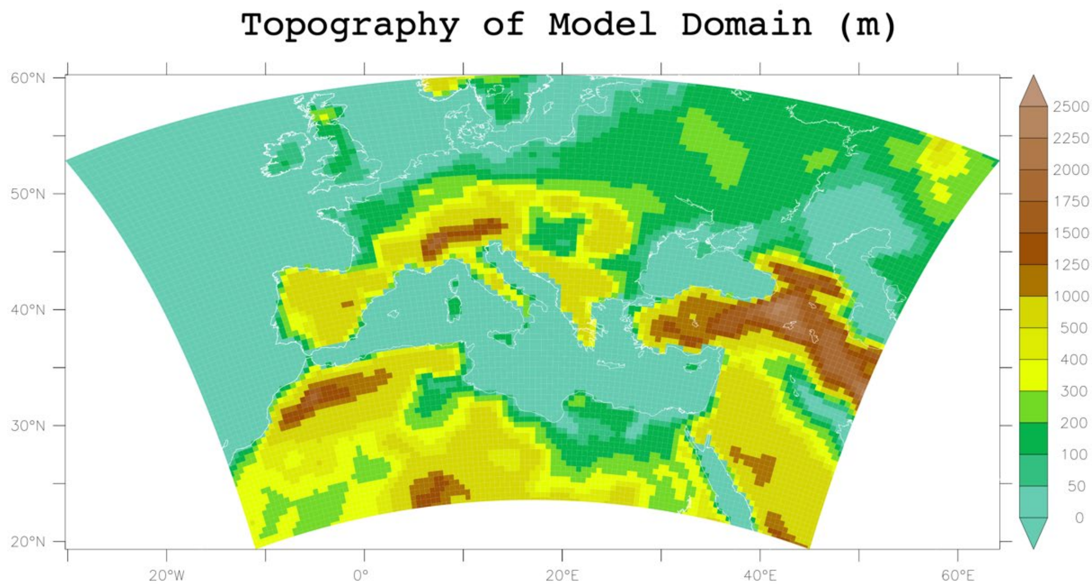

Figure 1. Topography of the domain used in numerical simulations.

Within 16 Med-CORDEX simulations, our model output has a good agreement with observations, in terms of precipitation extremes and temperature for the current climate [30]. The comparison of Med-CORDEX simulations were based on a daily analysis for extremes, and our simulation is one of those performing well, validated with daily precipitation extremes observations and ERA-Interim [31] reanalysis. These are widely discussed in the cited study and out of the main scope of this paper. However, a validation of ERA-Interim-based (European Centre for Medium-Range Weather Forecasts (ECMWF)'s previous reanalysis) RegCM simulation (to reflect "perfect" boundary conditions) with ECMWF's 5th generation reanalysis (ERA5) [32] also reveals that the model can capture the main characteristics of the spatial pattern of heavy precipitation quite well (Figure 2). There are intensity differences along coastlines with high mountain ranges, but it is important to note a probable factor on these differences; the horizontal resolution of ERA5 is higher than our RegCM simulation.

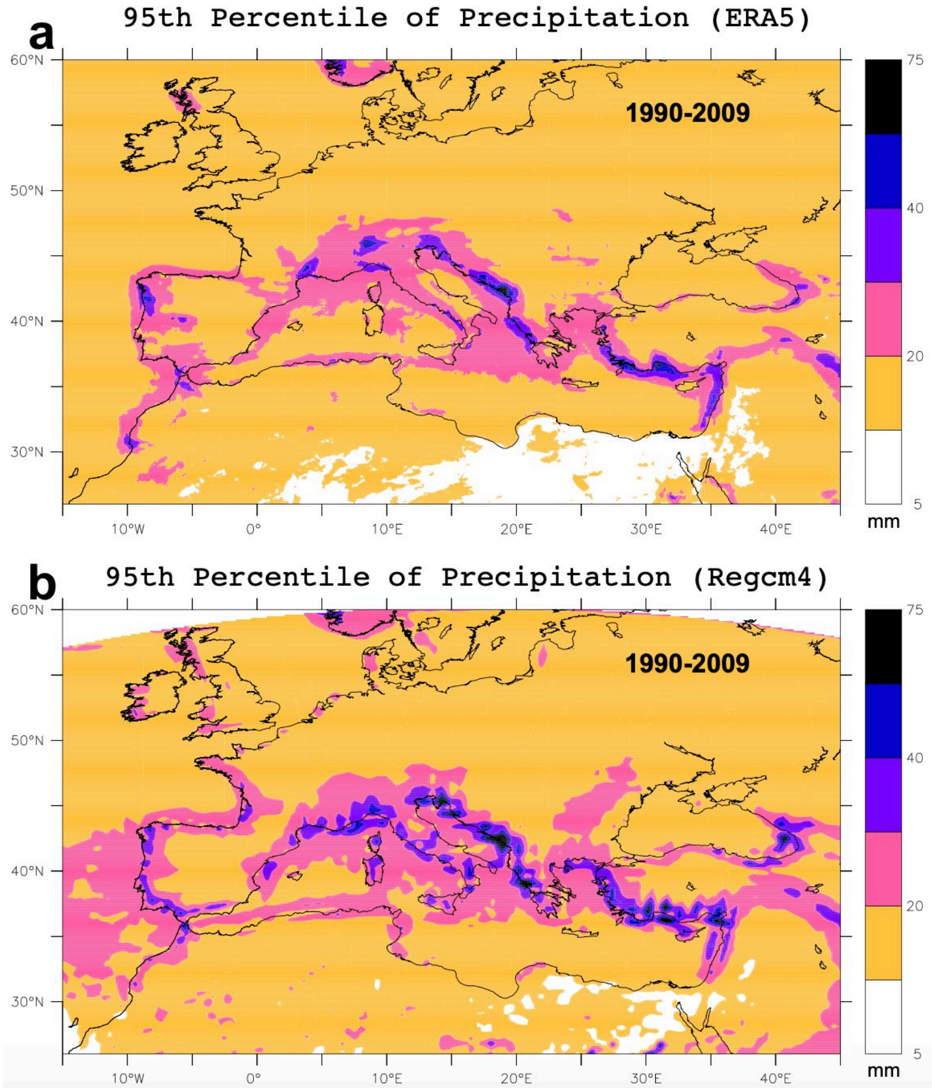

Figure 2. 95th percentile of precipitation for (**a**) ERA5 and (**b**) RegCM4 for 1990–2009.

Current severe convective weather forecasting approach focuses on the favorable environmental conditions in terms of thermodynamics and kinematics, and the atmospheric processes resulting in a possible overlap of these conditions. Necessary conditions for a thunderstorm are instability, moisture, and lift [33]. An additional factor, vertical wind shear, is essential for organized storms such as supercells or mesoscale convective systems. For example, very large hail (diameter larger than 5 cm) occurs almost exclusively with supercells, and supercells are more likely when the thunderstorm requirements exist and meanwhile, the vectoral difference of 10 m winds and winds 6 km above the surface is larger than 20 m/s [34]. This approach and thresholds for severe thunderstorm environments are also validated for cases around the region of interest [12]. From the thunderstorm requirements, instability and moisture can be represented by CAPE. Lift is the most challenging one due to the uncertainty in mesoscale processes. Low CIN, or existence of convective precipitation flux (cumulus parameterization triggering), can be used for representing the lift. Since a precise CIN calculation requires a high number of vertical levels in the boundary layer of the atmosphere, the latter approach is preferred in this study.

For the analysis of severe convective storm environments, instantaneous 12 UTC data for each day is used. The vast majority of the severe convective storms in the region occur between 12 UTC and 18 UTC, as shown by different sources of data, such as large hail observations across Europe [35], tornado observations across Europe [36], and radar-based thunderstorm analysis over northwestern Italy [37]. This timing is also the most close segment of the day for diurnal heating maxima for the whole domain, which is important in terms of convective initiation and maximization of instability. Since we aim to capture the environments prior to most of convective storm occurrence (so that the environment will favor the storms, but be less affected by their outcomes such as stabilization after CAPE release), we choose 12 UTC. However, the storms over the sea surface are not essentially dependent on diurnal cycle as most of the ones over the land are. So, there are parts of the domain with a different diurnal peak of the day, not only over the seas, but also some land areas, especially near the coasts. Nevertheless, our analysis corresponds to daytime severe thunderstorm environments which virtually cover most of the cases.

CAPE calculations are done using the most unstable parcel in a column of atmosphere. For vertical wind shear, horizontal wind components for each level are linearly interpolated in accordance with the geopotential height field of pressure levels. For convective initiation, the approach followed is the existence of convective precipitation rate.

The number of occasions with co-occurrence of sufficient CAPE (>100 J/kg) and severe convection favoring thresholds of deep-layer shear (bulk shear obtained from 10 m to 6 km above ground winds) are calculated. The number of vertical levels is crucial in CAPE calculations, and it could be better if we had more levels for more precise CAPE. However, as we use this metric mainly to separate unstable environments from stable ones, rather than to measure the degree of instability, current value is enough for our purposes.

The five proxies (overlapping conditions) extracted from the model output are given in Table 1. Basically, we use two thresholds for CAPE (100 and 500 J/kg) and two for shear (15 and 20 m/s bulk shear between 2 m and 6 km wind above surface). The more uncertain convective initiation factor is separately evaluated with three proxies (ending with letter "R"). The relationship of these proxies can be visualized as a Venn diagram (Figure 3). From the five proxies, "SEVere storm Environment without lift algorithm" (SevE) contains all others, while "SUPercell Environment with convective Rain" (SupER) is a subset of "SEVere storm Environment with convective Rain" (SevER) and "SUPercell Environment without lift algorithm" (SupE). "SUPercell Environment with convective Rain and High Instability" (SupERHI) is the smallest subset of all other proxies, with the highest thresholds.

The method is based on analyzing how future climate conditions differ from today's, in terms of number of favorable environments for each horizontal grid point. The future climate is divided into three periods of 20 years each, and compared with the 20 years representing the present climate as following:

$$\#FE\ 2040\sim2059—\#FE\ 1990\sim2009$$

$$\#FE\ 2060\sim2079—\#FE\ 1990\sim2009$$

$$\#FE\ 2080\sim2099—\#FE\ 1990\sim2009$$

where "#FE" is the number of favorable environments. Then, the values are divided by 20 to obtain annual averages. All values used in the results are annual average number of days (in terms of daytime environments).

Table 1. Proxies used in the study.

Proxy Name	MUCAPE	0–6 km Wind Shear	Convective Initiation	Description
SevE	≥100 J/kg	≥15 m/s	-	Severe storm environment without lift algorithm
SupE	≥100 J/kg	≥20 m/s	-	Supercell environment without lift algorithm
SeveR	≥100 J/kg	≥15 m/s	Conv. Prec. > 0	Severe storm environment with convective rain
SupeR	≥100 J/kg	≥20 m/s	Conv. Prec. > 0	Supercell environment with convective rain
SupeRHI	≥500 J/kg	≥20 m/s	Conv. Prec. > 0	Supercell environment with convective rain and high instability

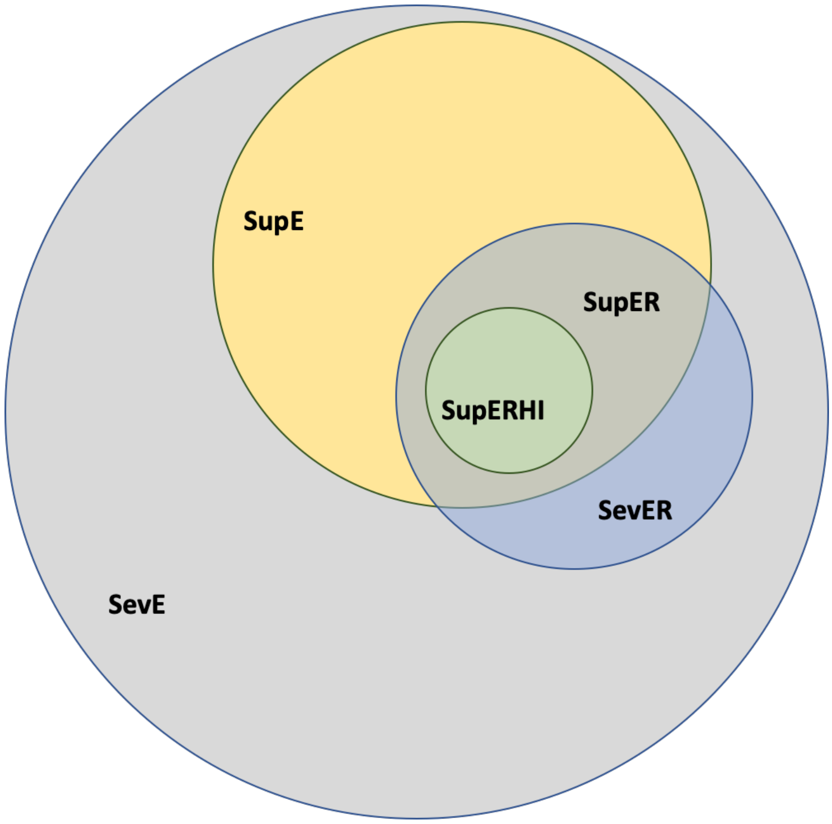

Figure 3. The proxies used in the study (definitions given in Table 1). Areas do not necessarily represent the number of cases.

3. Results

The results will be given in three subsections. In the first one, we will keep the lift factor aside and evaluate how the combinations of only latent instability and vertical wind shear change throughout the 21st century. In the second subsection, these environments with model-produced convective precipitation will be presented. In the last one, the theme is seasonality.

3.1. Proxies with Latent Instability and Vertical Wind Shear Combination Only

Sufficient latent instability with high deep-layer shear are the two main components of a severe thunderstorm environment. Leaving the more uncertain lift factor aside, these two ingredients can be conceptualized as the co-occasions of CAPE ≥ 100 J/kg and 0–6 km SHEAR ≥ 15 m/s at one grid point, what we will call "severe thunderstorm environments" or "SevE" from now on. Such high wind shear environments favor organization of thunderstorms, leading to mesoscale convective systems (MCSs), or other forms of organized convection. The CAPE threshold is relatively lower than what is observed for a typical severe thunderstorm, but it is known that lower resolution models underestimate the latent instability, and thunderstorms can occur with these minimal values of CAPE [14]. Also, these values are assured to cover low-CAPE—high-shear environments, which are common in the region especially during wintertime [15].

The SevE in the present climate is simulated densely over North Africa (Figure 4a), reaching more than once in every 10 days in a year, on average. It is important to note that this proxy does not represent how frequent the severe thunderstorms should occur indeed, since it does not include the crucial lift factor. However, it is important to evaluate it separately, to assess the change when lift is included. The Central and Eastern sections of the Mediterranean Sea also have high SevE values, well over 25 days in a year (Figure 4a). The SevE decreases in Europe from west to east, diminishing gradually towards Russia (Figure 4a).

Throughout the 21st century, SevE reveals significant changes especially around the coasts of the Mediterranean Sea (Figure 4b–d). Annual average days with SevE cases will increase to more than 15 in parts of Southern Turkish coasts by 2040–2059, and consistently stay at those values for the rest of the century. The Northern Adriatic, offshore Libya, and Tunus, as well as the Alboran Sea are other hot spots for future SevE increases. Parts of the Eastern Mediterranean will experience a few days increase in the middle of the century, and again a few days decrease afterwards. Inner parts of Western Europe have decreases in future simulations.

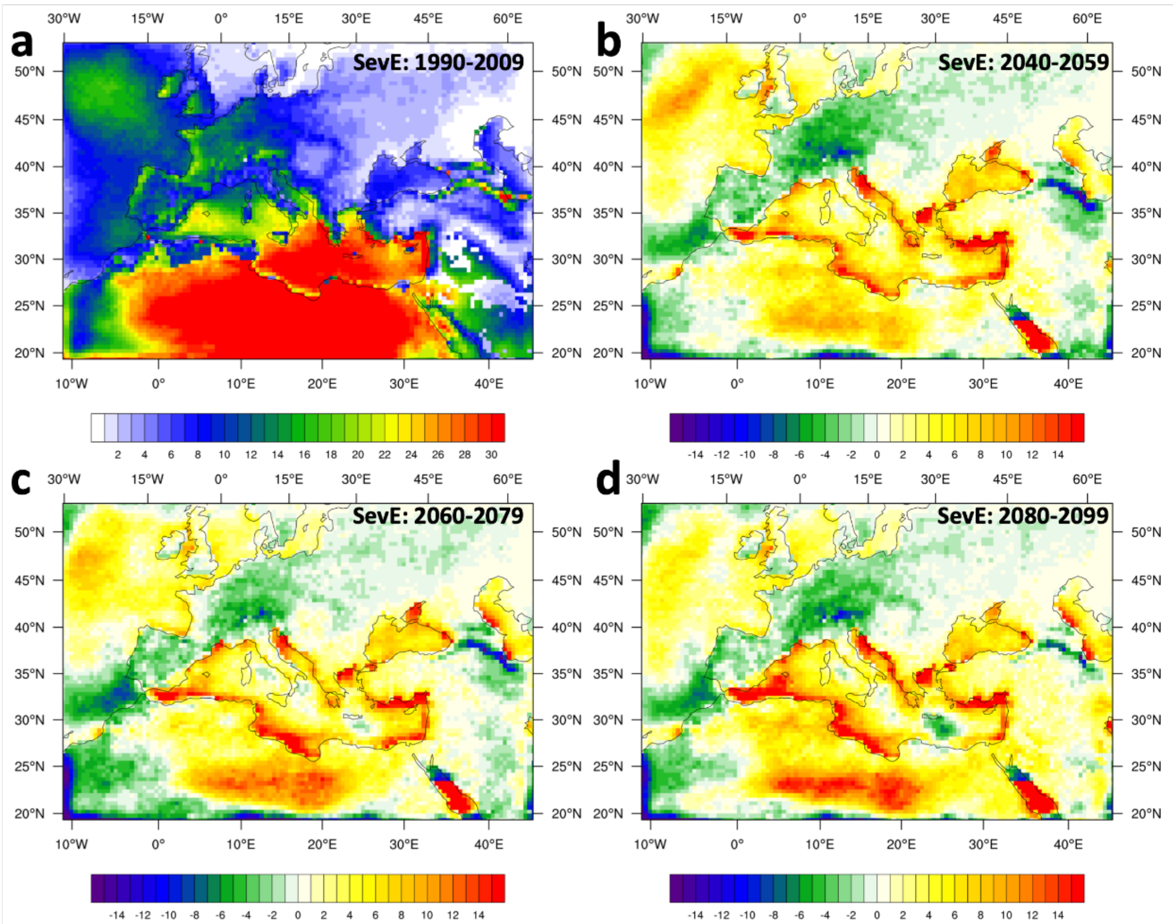

Figure 4. (**a**) Annual average number of days with CAPE ≥ 100 J/kg AND 0–6 km SHEAR ≥ 15 m/s (SevE) for 1990–2009, (**b**) changes in average number of days with SevE for 2040–2059, (**c**) changes in average number of days with SevE for 2060–2079, (**d**) changes in average number of days with SevE for 2080–2099.

Increasing the deep-layer shear variable to 20 m/s, we aim to seek a specific severe thunderstorm type, defined as "supercell environment", or "SupE". Such high shear overlapping with instability does not essentially result in supercell formation, but it is known that they are more likely to occur within these conditions once the convective initiation is satisfied. The combination of CAPE ≥ 100 J/kg and 0–6 km SHEAR ≥ 20 m/s includes a subsection of the previously analyzed SevE cases, while it also may contain nonsupercell severe thunderstorms such as derechoes and other forms of well-organized convection. The lift factor is still excluded in this proxy, meaning that the atmosphere has the potential to favor supercells, but it is not warranted that the parcel will rise to its level of free convection, and any storm may or may not form in reality.

In the present climate, the SupE is less than half of the SevE in most of the domain (Figure 5a), on the other hand, giving a similar pattern regarding the spatial distribution. Remarkable areas include North Africa, Central and Eastern Mediterranean, as well as local segments near Caucasus. In the future, the changes are less evident than those for SevE, but still highlight the Mediterranean coasts with annual average increases of cases as high as 10 days (Figure 5b–d). A 2–3-day decrease in noncoastal continental Europe in 2040–2059 weakens later in the century.

Here, it should be noted that due to the fact supercells are rare phenomena, the 1–2-day changes can obviously be taken as the variability of the climate, rather than indicating a statistically significant signal. The high values near Caucasus diminish in future simulations. Also, continental Europe, especially the region surrounding the The Alps, reveals noticeable decrease. Nevertheless, both SevE and SupE show similar patterns, but the current climate, as well as changes in the future periods, is less emphasized with SupE.

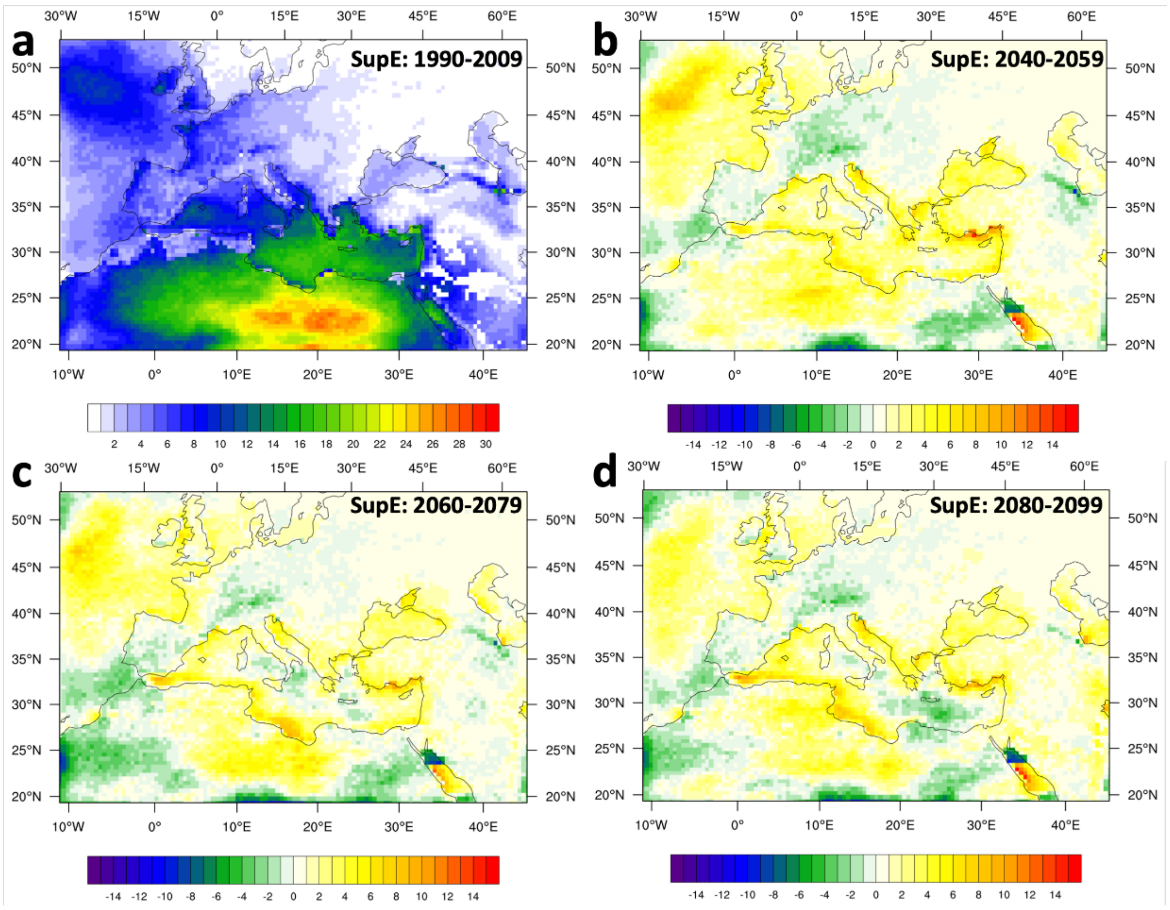

Figure 5. (**a**) Annual average number of days with CAPE ≥ 100 J/kg AND 0–6 km SHEAR ≥ 20 m/s (SupE) for 1990–2009, (**b**) changes in average number of days with SupE for 2040–2059, (**c**) changes in average number of days with SupE for 2060–2079, (**d**) changes in average number of days with SupE for 2080–2099.

3.2. Proxies for Severe Thunderstorms and Supercells, with Simulated Convective Precipitation

Adding the convective precipitation factor to the diagnostics analyzed above, we aim to approximate the anticipated severe thunderstorm-producing and supercell-producing settings. The "SevER" proxy refers to the cases with CAPE ≥ 100 J/kg and 0–6 km SHEAR ≥ 15 m/s, as well as convective precipitation rate above zero. SevER is a subset of SevE, so the number of days with these conditions are lower, because the convective initiation does not take place in most of the favorable environments (Figure 6a). The dramatic decrease from SevE to SevER shows how important and scarce the lift factor is, which is the missing ingredient for thunderstorms in the atmosphere most of the time.

Severe convective storm environments in the present climate are depicted in Figure 6a. The SevER extends across all of Europe and the Mediterranean Sea, Turkey, and further east. The overall pattern and quantitative values are quite in agreement with those calculated with 1981–2000 ERA-Interim data [8]. Our simulation has slightly higher resolution than what is provided by ERA-Interim's 0.75 degrees horizontal grid spacing, so the extremes are better covered. The Mediterranean Sea and its surroundings, as well as Central Europe, are well fit, but there are positive biases around the Atlantic Ocean and northern Europe (Figure 6a). One other reason for differences, especially around complex topography, can be the potentially unrepresentative low-level wind field in ERA-Interim, leading to weaker vertical wind shear diagnostics [12]. Overall, the most impressive hot spots include the Eastern Mediterranean, reaching as high as 15 days with SevER cases, and the Caucasus region with northeast Turkey, experiencing an even higher number of days than that. Truly, northeastern Turkey has curiously active weather in terms of severe convection [16,19,38].

A further analysis for SevER is performed with ERA5 data for 1990–2009. Here, mainly due to its higher resolution, the number of cases are higher than what is simulated by RegCM and Era-Interim (Figure 7), but the spatial pattern agrees with the simulation. The limitation of coarse resolution data is evident, suggesting that there could be a much higher number of days with severe storm environments than what is simulated both for current and future simulations. Especially coastlines with high mountain ranges indicate higher extremes in ERA5, which are emphasized in southwest-looking coasts, showing a topographical enhancement likely during Mediterranean cyclones. Indeed, Mediterranean cyclones are found to be an important contributor of severe weather in the region (e.g., in Turkey [39]). There is also another mechanism enhancing the vertical wind shear around upwind parts of mountain ranges, which can be another explanation in the mesoscale [40].

SevER cases significantly increase over the Mediterranean Sea and nearby coastal areas throughout the 21st century (Figure 6b–d). In the southwest-facing segments of the Turkish coast, the rise reaches 10 days more than today. On the other hand, there is 1–3 days decrease around Central Europe, even more than that around the noteworthy Caucasus region. These results are partially different than what was found by some previous studies. For example, increases in severe storm environments over central and eastern Europe were found in a study with Coordinated Downscaling Experiment - European Domain (EURO-Cordex) ensemble, under RCP8.5 conditions for 2071–2100 [8]. The same study also suggests that no important change occurs over Central and Eastern Mediterranean. The uncertainty of this issue regarding the geographical features of the Mediterranean Sea and surroundings was discussed earlier in another study [1].

One of the contributors for higher number of instability days (hence SevER) in our simulations can be the SST. A comparison of SST between ERA5 and HadGEM (the input used in our RegCM simulation) reveals similar results, with noted differences around the Black Sea, some Mediterranean coasts, and north of the British and Irish Islands (Figure 8). This can partially explain the coastal increases, and might have implications for future simulations also, which are run with HadGEM2 data.

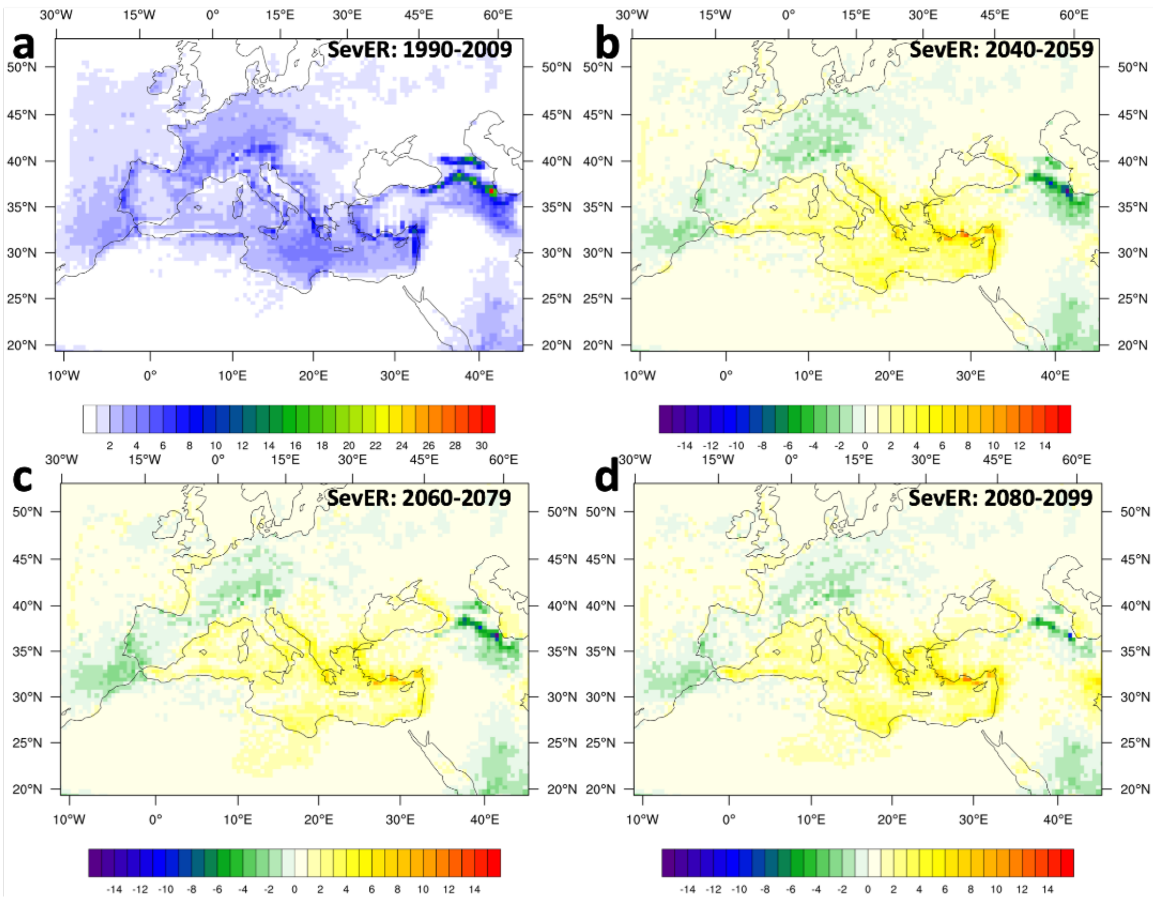

Figure 6. (**a**) Annual average number of days with CAPE ≥ 100 J/kg AND 0–6 km SHEAR ≥ 15 m/s AND convective precipitation rate > 0 mm/h (SevER) for 1990–2009, (**b**) changes in average number of days with SevER for 2040–2059, (**c**) changes in average number of days with SevER for 2060–2079, (**d**) changes in average number of days with SevER for 2080–2099.

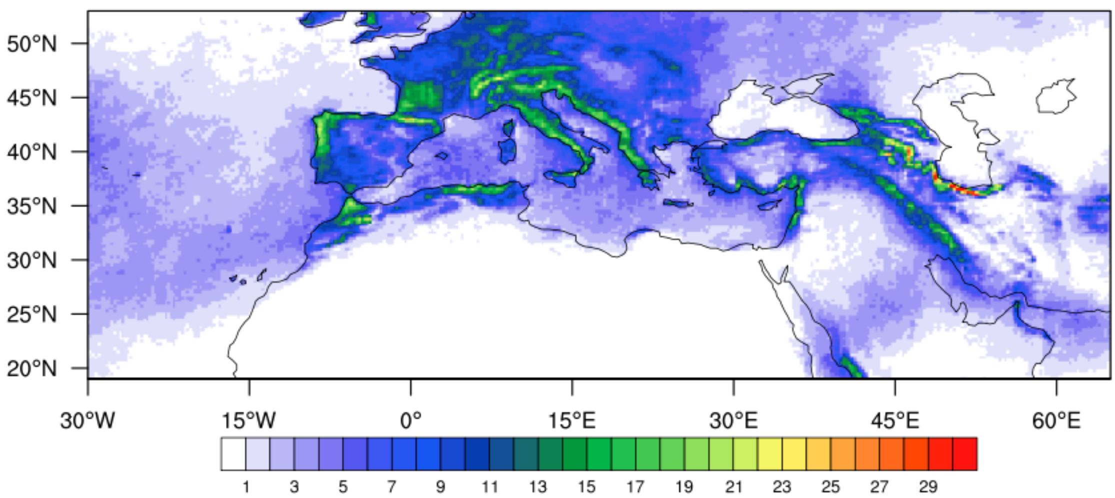

Figure 7. Annual average number of SevER cases calculated with ERA5 data for 1990–2009**.**

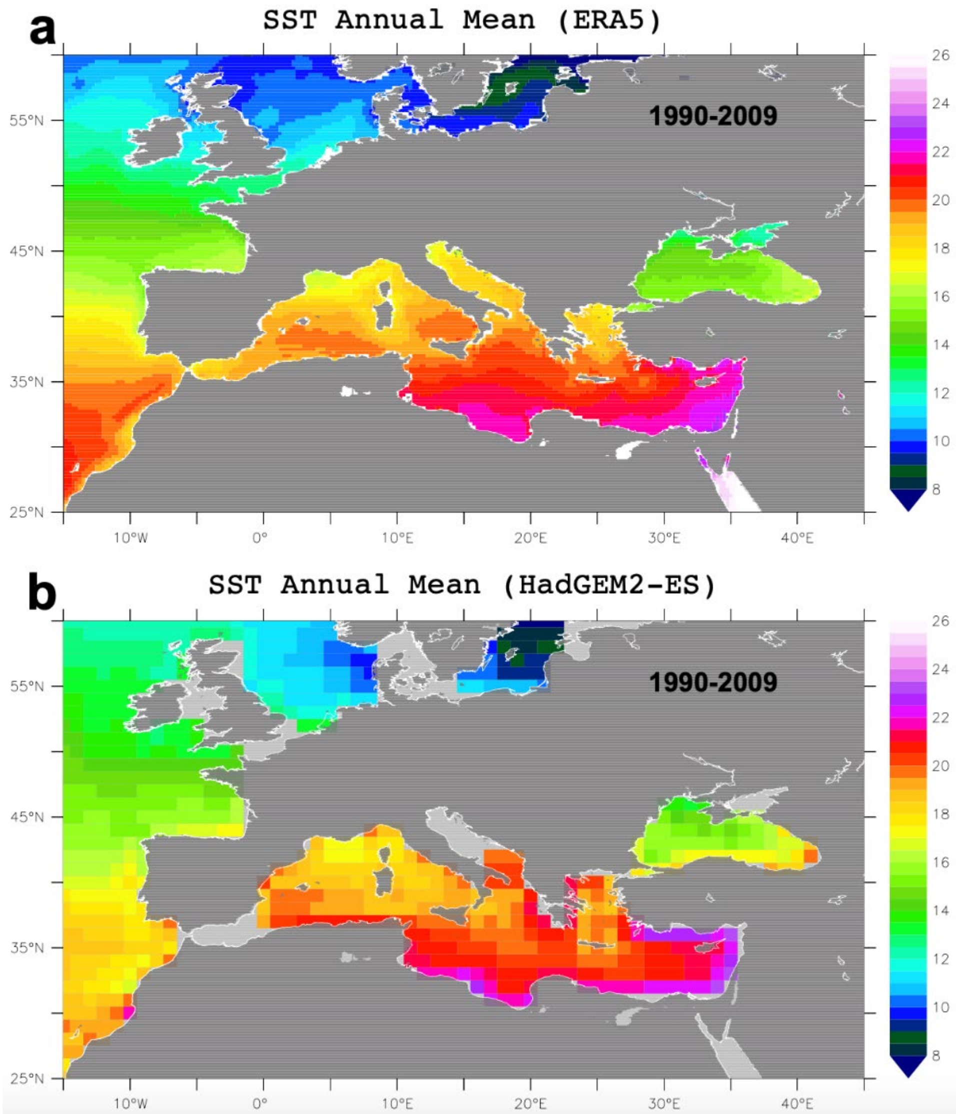

Figure 8. Annual average sea surface temperature for (**a**) ERA5 and (**b**) RegCM input for 1990–2009.

Using the same approach as SevER with increasing the shear threshold to 20 m/s, we obtain "SupER" cases. For a given location, supercells are rare storms, and this shows up in the current climate results (Figure 9a). Most of the cases are fit between 30 and 40 degrees latitude, as these are midlatitude phenomena. The annual average number of SupER is usually 1 or 2 within this belt, which is quite realistic. The Central Mediterranean and coasts facing south or west have more frequent SupER cases. One other hot region is the Caucasus, which actually includes parts of Europe with the highest number of days with lightning strikes [41] and relatively high number of tornadoes despite elevated terrain and underreporting issues based on lower population density [38].

Future conditions bring even more SupER cases around the Mediterranean, especially the coasts (Figure 9b–d). By the end of the century, south- and west-looking coastal areas around the Mediterranean Sea experience two times more SupER than today. Turkey and Greece in particular, show 1–4 days increase signal. On the other hand, there are regions with slight decreases, such as southwest parts of the Iberian Peninsula. Peak in Caucasus Region observes a decrease between 2040 and 2059 (Figure 9b), and a return back to current values between 2080 and 2099 (Figure 9d).

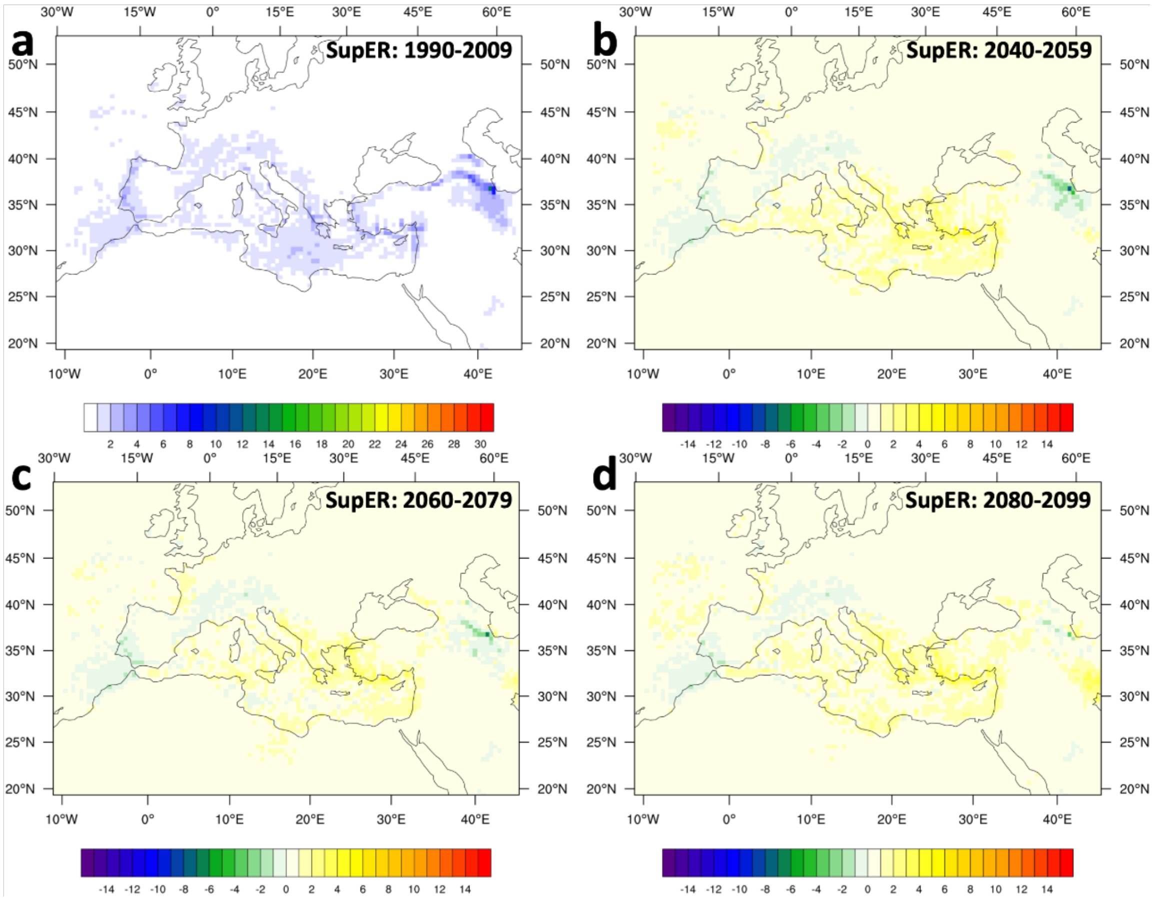

Figure 9. (**a**) Annual average number of days with CAPE ≥ 100 J/kg AND 0–6 km SHEAR ≥ 20 m/s AND convective precipitation rate > 0 mm/h (SupER) for 1990–2009, (**b**) changes in average number of days with SupER for 2040–2059, (**c**) changes in average number of days with SupER for 2060–2079, (**d**) changes in average number of days with SupER for 2080–2099.

Using the CAPE threshold as 500 J/kg instead of 100 J/kg, we calculate the SupERHI proxy. This diagnostic should potentially cover significant severe weather events, but it is very rare for these high CAPE values to overlap with very high wind shear values, given the coarse resolution of the model output. Eventually, there are only a few grid points having an annual average of SuperHI exceeding 1 day, and those are located unsurprisingly in the Caucasus region and its surroundings (Figure 10a). However, the Eastern and Central Mediterranean coasts do establish these rare occasions in the future simulations (Figure 10b–d). Meanwhile, some decrease of SupERHI in the Caucasus region is projected in the middle of the century, slightly recovering by 2080–2099.

3.3. Seasonal Changes in Severe Thunderstorm Environments

To analyze the severe thunderstorm environments and their evolution, a seasonal look is useful. Here, we use slightly shifted seasons in order to discriminate the thunderstorm environments in the region better. The seasonality of SevE basically suggests a peak over the sea and ocean in the cold season, with a continental peak in the warm season as expected (Figure 11a,d,g,j). The Saharan maxima is evident in spring, leaving the summer to the subtropical high. The Eastern Mediterranean has its own peak between October and March, while continental Europe has SevE mostly from April to September.

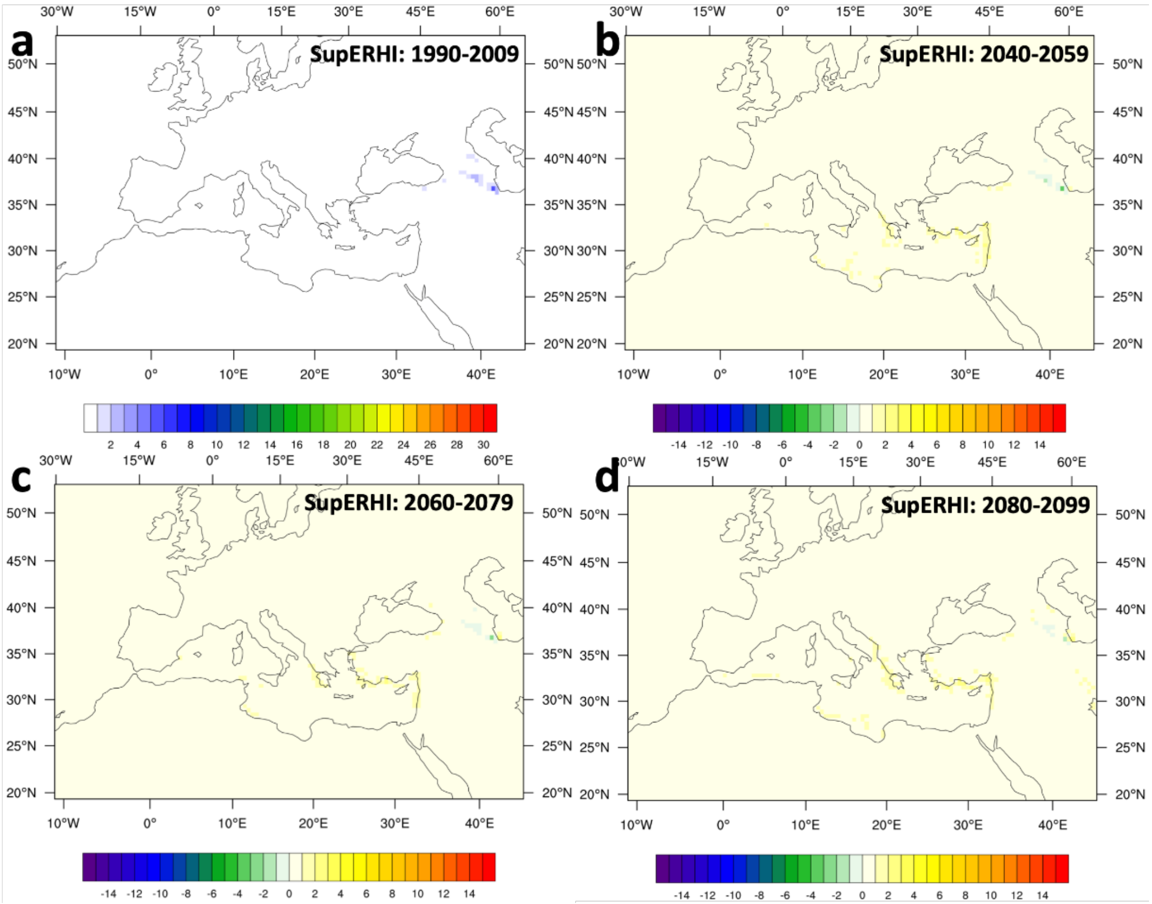

Figure 10. (**a**) Annual average number of days with CAPE ≥ 500 J/kg AND 0–6 km SHEAR ≥ 20 m/s AND convective precipitation rate > 0 mm/h (SupERHI) for 1990–2009, (**b**) changes in average number of days with SupERHI for 2040–2059, (**c**) changes in average number of days with SupERHI for 2060–2079, (**d**) changes in average number of days with SupERHI for 2080–2099.

Changes in the SevE have different aspects in different seasons and regions. First, a gradual increase in January, February, and March (JFM) around the broad Mediterranean and its surroundings is clear (Figure 11). For instance, the changes in these months seem to contribute to the overall increase in the region as seen in Figure 4 mostly. The April, May, and June (AMJ) and July, August, and September (JAS), on the other hand, suggest a decrease in SevE in most of western and central Europe. This is likely due to the expanding subtropical high towards Europe in the warm season, limiting the occasions of instability and jets. The coastal belts around the Eastern Mediterranean take a distinct increase in October, November, and December (OND). Warmer sea surface in these months could potentially increase the instability days here.

Adding the lift factor with inclusion of convective precipitation to the criteria, we have the seasonal distribution of severe thunderstorm environments (Figure 12). SevER cases populate a much smaller zone in JFM, when compared to SevE (Figure 12a vs. Figure 11a). This shows that although there is sufficient CAPE, it is not realized as an occurrence of a thunderstorm. The bulk of the precipitation in these months occurs due to fronts associated with midlatitude cyclones. The JFM SevER cases are most simulated over the Eastern Mediterranean, which is consistent with what is observed in real life. In the future, these environments are more frequent in this hotspot, even expanding the region (Figure 12b,c).

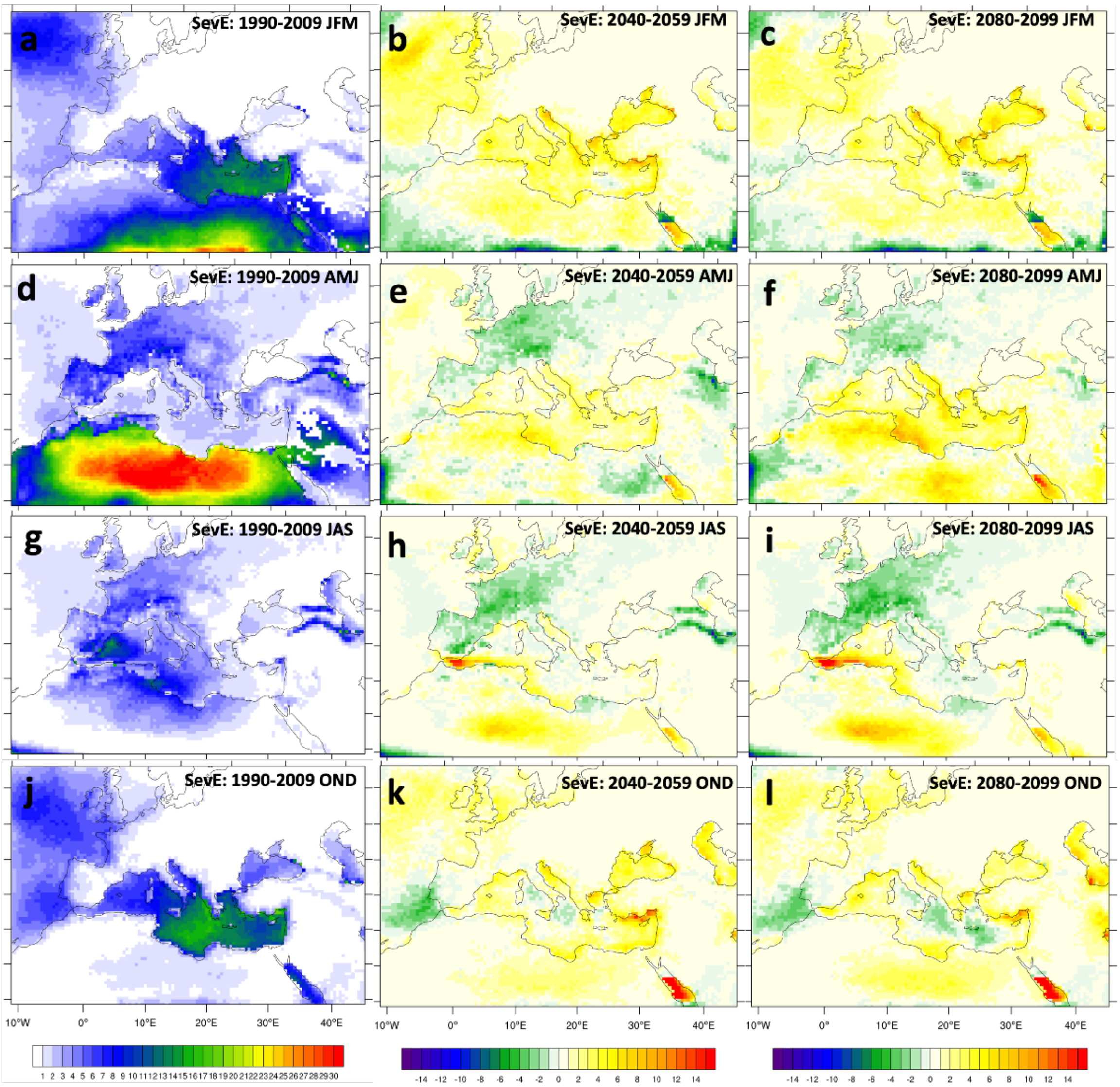

Figure 11. (**a**) Annual average number of days with CAPE ≥ 100 J/kg AND 0–6 km SHEAR ≥ 15 m/s (SevE) for January, February, and March (JFM) of 1990–2009, (**b**) changes in average number of days with SevE for JFM 2040–2059 ,(**c**) changes in average number of days with SevE for JFM 2080–2099, (**d**) annual average number of days with SevE for April, May, and June (AMJ) of 1990–2009, (**e**) changes in average number of days with SevE for AMJ 2040–2059, (**f**) changes in average number of days with SevE for AMJ 2080–2099, (**g**) annual average number of days with SevE for July, August, and September (JAS) of 1990–2009, (**h**) changes in average number of days with SevE for JAS 2040–2059, (**i**) changes in average number of days with SevE for JAS 2080–2099, (**j**) annual average number of days with SevE for October, November, and December (OND) of 1990–2009, (**k**) changes in average number of days with SevE for OND 2040–2059, (**l**) changes in average number of days with SevE for OND 2080–2099.

In contrast with JFM, AMJ comes with a completely different pattern: Mediterranean thunderstorms diminish, while parts of continental Europe, Turkey, and further east towards the Caspian Sea experience most of the severe thunderstorm environments (Figure 12d). This is the primary high season for Caucasus thunderstorms. It seems that midcentury simulations reveal a decrease in SevER environments in parts of Europe and Azerbaijan, while slight increases in Balkans, Turkey, and coastal North Africa are expected (Figure 12e). Later, for 2080–2099, the mentioned decreases are limited, while the increases persist (Figure 12f).

SevER in JAS is most frequent in Central and Western Europe (Figure 12g). However, these decrease in the future climate (Figure 12h,i). The Caucasus decrease is also evident for these months.

Finally, OND, the high season for the entire Mediterranean Sea—coasts in particular—appears to strengthen the frequency of SevER conditions in the future (Figure 12j–l).

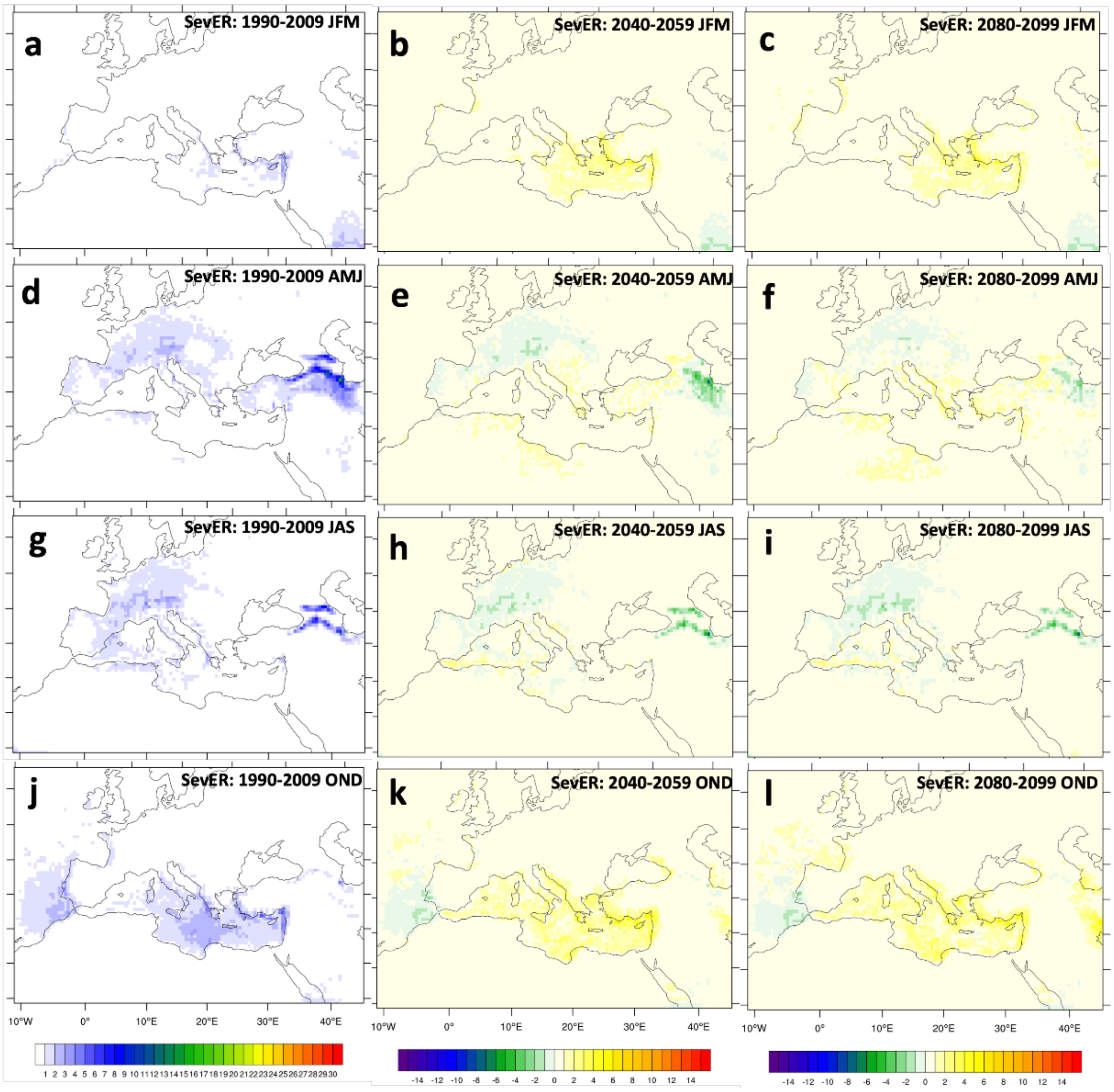

Figure 12. (**a**) Annual average number of days with CAPE ≥ 100 J/kg AND 0–6 km SHEAR ≥ 15 m/s AND convective precipitation rate > 0 mm/h (SevER) for January, February, and March (JFM) of 1990–2009, (**b**) changes in average number of days with SevER for JFM 2040–2059, (**c**) changes in average number of days with SevER for JFM 2080–2099, (**d**) annual average number of days with SevER for April, May, and June (AMJ) of 1990–2009, (**e**) changes in average number of days with SevER for AMJ 2040–2059, (**f**) changes in average number of days with SevER for AMJ 2080–2099, (**g**) annual average number of days with SevER for July, August, and September (JAS) of 1990–2009, (**h**) changes in average number of days with SevER for JAS 2040–2059, (**i**) changes in average number of days with SevER for JAS 2080–2099, (**j**) annual average number of days with SevER for October, November, and December (OND) of 1990–2009, (**k**) changes in average number of days with SevER for OND 2040–2059, (**l**) changes in average number of days with SevER for OND 2080–2099.

4. Discussion and Conclusions

Our results suggest that, in summary, the number of days with daytime environments favorable for severe convective storms will generally increase over the Mediterranean Sea, and slightly decrease over Western Europe in the late 21st century. Coastal areas around the Mediterranean Sea are found to experience the highest increase in severe convective storm environment frequencies. However, it should be noted that these results rely on one simulation suite only, and since the studied problem reveals high uncertainty, these should be taken with caution. Our simulations are one of the successful ones in capturing extremes within the Med-CORDEX simulations, but any other simulation with different driving general circulation model, different model dynamics, and physical schemes (for instance, especially convective parameterization choice due to the role in convective initiation assumption here) may produce considerably different results. Here, it is important to note that, since the common practice among climatologists is not storing instantaneous 3D data with many vertical levels (due to its high volume), data availability is limited for performing severe convective storm environment analysis such as the one done this study. If more model output with sufficient vertical levels—and preferably higher resolution—could be available, the uncertainties could better be quantified.

As the global temperature increase results in more evaporation and more water vapor in the atmosphere, CAPE is enhanced. The sea surface temperature is one of the main contributors to this, as most of the increase over the Mediterranean happens in late warm season. The SST bias has the potential to affect the results in terms of instability contributions. This raises the need for coupled models more properly simulating the future climate [42].

It is well known that the variation of the expected temperature increase through latitudes are not constant. Higher latitudes get much warmer, and therefore weaken the gradient between the poles and tropics. This results in weaker jets and weaker vertical wind shear. This potentially decreases the number of severe thunderstorm environments, which is one of the contributing factors in the slight decrease over continental Europe.

The higher increase around the coastal zones is noteworthy and needs further remarks. The reason for these increases is not known and needs further investigation. An explanation can be one recent study, highlighting that such coastal zones may have their own kinematic features. Modification of low-level winds may result in higher shear in the proximity of mountains [40]. Given the rise in sea surface temperatures, the frequency of occasions with CAPE threshold exceedance increases in the future climate. The other factor, wind shear, is likely to be reduced, but the rise in CAPE days might compensate the fall in shear days locally. Around the coasts, the topographical modification of shear would play a role on keeping shear days high. This potentially explains why a decrease of vertical wind shear due to weakening jets might not totally reduce the number of sheared occasions around the coasts with adjacent high mountain ranges, such as southern Turkish coasts.

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

Funding: This study is partially funded by the Scientific Research Projects of Istanbul Technical University, Research Grant ID 36116 and 41536.

Acknowledgments: We thank numerous scientists who contributed to the RegCM code, ERA5 data, and available HadGEM2 data used as boundary conditions. We also thank two anonymous reviewers and the editor for their comments improving the paper.

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

References

1. Brooks, H. Severe thunderstorms and climate change. *Atmos. Res.* **2013**, *123*, 129–138. [CrossRef]
2. Allen, J.T.; Karoly, D.J.; Walsh, K.J. Future Australian severe thunderstorm environments. Part II: The influence of a strongly warming climate on convective environments. *J. Clim.* **2014**, *27*, 3848–3868. [CrossRef]
3. Trapp, R.J.; Diffenbaugh, N.S.; Brooks, H.E.; Baldwin, M.E.; Robinson, E.D.; Pal, J.S. Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 19719–19723. [CrossRef]
4. Diffenbaugh, N.S.; Scherer, M.; Trapp, R.J. Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 16361–16366. [CrossRef]
5. Romps, D.M.; Seeley, J.T.; Romps, D.M. The effect of global warming on severe thunderstorms in the United States. *J. Clim.* **2015**, *28*, 2443–2458.
6. Ni, X.; Zhang, F.; Zhang, Q. Decreasing trend in severe weather occurrence over China during the past 50 years. *Sci Rep.* **2017**, *7*, 42310.
7. Zhang, Q.; Li, W.; Li, J.; Zou, T. Responses of hail and storm days to climate change in the Tibetan Plateau. *Geophys. Res. Lett.* **2018**, *45*, 4485–4493.
8. Púčik, T.; Groenemeijer, P.; Rädler, A.T.; Tijssen, L.; Nikulin, G.; Prein, A.F.; van Meijgaard, E.; Fealy, R.; Jacob, D.; Teichmann, C. Future changes in European severe convection environments in a regional climate model ensemble. *J. Clim.* **2017**, *30*, 6771–6794. [CrossRef]
9. Zamora, R.A.; Korty, R.L.; Huber, M. Thermal stratification in simulations of warm climates: A climatology using saturation potential vorticity. *J. Clim.* **2016**, *29*, 5083–5102. [CrossRef]
10. Brogli, R.; Kröner, N.; Sørland, S.L.; Lüthi, D.; Schär, C. The role of hadley circulation and lapse-rate changes for the future European summer climate. *J. Clim.* **2019**, *32*, 385–404. [CrossRef]
11. Tilev-Tanriover, S.; Schultz, D.M.; Kadioglu, M. Climatology of severe convective storm environments from ERA-interim. In Proceedings of the European Conference on Severe Storms 2015, Wiener Neustadt, Austria, 14–18 September 2015.
12. Kahraman, A.; Kadioglu, M.; Markowski, P.M. Severe convective storm environments in Turkey. *Mon. Weather Rev.* **2017**, *145*, 4711–4725. [CrossRef]
13. Brooks, H.E. Proximity soundings for severe convection for Europe and the United States from reanalysis data. *Atmos. Res.* **2009**, *93*, 546–553. [CrossRef]
14. Brooks, H.E.; Lee, J.W.; Craven, J.P. The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.* **2003**, *67–68*, 73–94. [CrossRef]
15. Brooks, H.; Battaglioli, F.; Croad, H.; Cumming, R.; Martin, E. High-shear/low-CAPE environments in reanalysis data. In Proceedings of the ECSS 2019, Krakow, Poland, 4–8 November 2019.
16. Kahraman, A.; Markowski, P.M. Tornado climatology of Turkey. *Mon. Weather Rev.* **2014**, *142*, 2345–2352. [CrossRef]
17. Sioutas, M.V. A tornado and waterspout climatology for Greece. *Atmos. Res.* **2011**, *100*, 344–356. [CrossRef]
18. Sioutas, M.V.; Doe, R.; Michaelides, S.; Christodoulou, M.; Robins, R. Meteorological conditions contributing to the development of severe tornadoes in southern Cyprus. *Weather* **2006**, *61*, 10–16. [CrossRef]
19. Kahraman, A.; Tilev-Tanriover, Ş.; Kadioglu, M.; Schultz, D.M.; Markowski, P.M. Severe hail climatology of Turkey. *Mon. Weather Rev.* **2016**, *144*, 337–346. [CrossRef]
20. Michaelides, S.C.; Savvidou, K.; Nicolaides, K.A.; Orphanou, A.; Photiou, G.; Kannaouros, C. Synoptic, thermodynamic and agroeconomic aspects of severe hail events in Cyprus. *Nat. Hazards Earth Syst. Sci.* **2008**, *8*, 461–471. [CrossRef]
21. Sioutas, M.; Meaden, T.; Webb, J.D.C. Hail frequency, distribution and intensity in Northern Greece. *Atmos. Res.* **2009**, *93*, 526–533. [CrossRef]
22. Vinet, F.; Bigot, V.; Petrucci, O.; Papagiannaki, K.; Llasat, M.C.; Kotroni, V.; Boissier, L.; Aceto, L.; Grimalt, M.; Pasqua, A.A.; et al. Mapping flood-related mortality in the Mediterranean Basin. Results from the MEFF v2.0 DB. *Water* **2019**, *11*, 2196. [CrossRef]
23. Tilev-Tanriover, Ş.; Kahraman, A.; Kadioğlu, M.; Schultz, D.M. Lightning fatalities and injuries in Turkey. *Nat. Hazards Earth Syst. Sci.* **2015**, *15*, 1881–1888. [CrossRef]
24. Dayan, U.; Ziv, B.; Margalit, A.; Morin, E.; Sharon, D. A severe autumn storm over the middle-east: Synoptic and mesoscale convection analysis. *Theor. Appl. Climatol.* **2001**, *69*, 103–122. [CrossRef]

25. Ruti, P.M.; Somot, S.; Giorgi, F.; Dubois, C.; Flaounas, E.; Obermann, A.; Dell'Aquila, A.; Pisacane, G.; Harzallah, A.; Lombardi, E.; et al. Med-CORDEX initiative for Mediterranean climate studies. *Bull. Am. Meteorol. Soc.* **2016**, *97*, 1187–1208. [CrossRef]
26. Giorgi, F.; Coppola, E.; Solmon, F.; Mariotti, L.; Sylla, M.B.; Bi, X.; Elguindi, N.; Diro, G.T.; Nair, V.; Turuncoglu, U.U.; et al. RegCM4: Model description and preliminary tests over multiple CORDEX domains. *Clim Res.* **2012**, *52*, 7–29. [CrossRef]
27. Grell, G.A. Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Weather Rev.* **1993**, *121*, 764–787. [CrossRef]
28. Kiehl, J.T.; Hack, J.J.; Bonan, G.B.; Boville, B.A.; Briegleb, B.P.; Williamson, D.L.; Rasch, P.J. *Description of the NCAR Community Climate Model (CCM3) (No. NCAR/TN-420+STR)*; University Corporation for Atmospheric Research: Boulder, CO, USA, 1996. [CrossRef]
29. Dickinson, R.E.; Henderson-Sellers, A.; Kennedy, P.J. *Biosphere-atmosphere Transfer Scheme (BATS) Version 1e as Coupled to the NCAR Community Climate Model (No. NCAR/TN-387+STR)*; University Corporation for Atmospheric Research: Boulder, CO, USA, 1993. [CrossRef]
30. Drobinski, P.; Da Silva, N.; Panthou, G.; Bastin, S.; Muller, C.; Ahrens, B.; Borga, M.; Conte, D.; Fosser, G.; Güttler, I.; et al. Scaling precipitation extremes with temperature in the Mediterranean: Past climate assessment and projection in anthropogenic scenarios. *Clim. Dyn.* **2018**, *51*, 1237–1257. [CrossRef]
31. Dee, D.P.; Uppala, S.M.; Simmons, A.J.; Berrisford, P.; Poli, P.; Kobayashi, S.; Andrae, U.; Balmaseda, M.A.; Balsamo, G.; Bauer, P.; et al. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* **2011**, *137*, 553–597. [CrossRef]
32. Hersbach, H.; Bell, B.; Berrisford, P.; Hiráhara, S.; Horányi, A.; Muñoz-Sabater, J.; Berrisford, P.; Nicolas, J.; Radu, R.; Scheper, D.; et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2049. [CrossRef]
33. Doswell, C.A.; Brooks, H.E.; Maddox, R.A. Flash flood forecasting: An ingredients-based methodology. *Weather Forecast.* **1996**, *11*, 560–581. [CrossRef]
34. Rasmussen, E.N.; Blanchard, D.O. A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Weather Forecast.* **1998**, *13*, 1148–1164. [CrossRef]
35. Púčik, T.; Castellano, C.; Groenemeijer, P.; Kühne, T.; Rädler, A.T.; Antonescu, B.; Faust, E. Large hail incidence and its economic and societal impacts across Europe. *Mon. Weather Rev.* **2019**, *147*, 3901–3916. [CrossRef]
36. Antonescu, B.; Schultz, D.M.; Lomas, F.; Kühne, T. Tornadoes in Europe: Synthesis of the observational datasets. *Mon. Weather Rev.* **2016**, *144*, 2445–2480. [CrossRef]
37. Davini, P.; Bechini, R.; Cremonini, R.; Cassardo, C. Radar-based analysis of convective storms over Northwestern Italy. *Atmosphere* **2012**, *3*, 33–58. [CrossRef]
38. Kivrak, B.; Kahraman, A. Tornadoes of northeastern Turkey. *Atmosphere* **2020**, *11*. submission under review.
39. Kahraman, A. Synoptic climatology of supercell-type tornado and very large hail days in Turkey. *Weather* **2020**, in press. [CrossRef]
40. Kahraman, A.; Markowski, P. The enhancement of vertical wind shear by tall mountains in convective storm environments. In Proceedings of the European Conference on Severe Storms (ECSS) 2015, Wiener Neustadt, Austria, 14–18 September 2015.
41. Enno, S.E.; Sugier, J.; Alber, R.; Seltzer, M. Lightning flash density in Europe based on 10 years of ATDnet data. *Atmos. Res.* **2020**. [CrossRef]
42. Turuncoglu, U.U.; Sannino, G. Validation of newly designed regional earth system model (RegESM) for Mediterranean Basin. *Clim. Dyn.* **2017**, *48*, 2919–2947. [CrossRef]