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Regional climate projections of heavy precipitation over the Balkan Peninsula

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Abstract— This article presents climate change projections of heavy (above a certain threshold) precipitation under the Representative Concentration Pathways RCP4.5 and RCP8.5 for the territory of the Balkan Peninsula. The focus is on convective rainfall which, if significant, can damage infrastructure and cause casualties. For this purpose, RegCM4.4.5 regional climate model with 20 km resolution was used for the periods 2021–2050 and 2071–2099 compared with the reference period 1975–2004. The change in the number of heavy rainfalls is determined by using the thresholds in the Meteoalarm program corresponding to the 'yellow' code. It is found that the largest changes in the number of convective precipitation events are in the coastal and mountainous areas. The increase in the number of cases of heavy rainfalls does not exclude the decrease in the amount of precipitation in these areas. This can be explained by the increase in the period in which these precipitations are possible due to the increase in temperatures.

Key-words: climate projections, heavy rainfalls, heavy convective rainfalls, RegCM, Meteoalarm

1. Introduction

The FP7 RAIN project (http://rain-project.eu/wp-content/uploads/2015/11/D2.3-Warning-Systems.pdf) notes the view expressed by stakeholders that critical infrastructure can be affected by convective events of high intensity and short duration. This is the reason why this work focuses on convective precipitation. This type of rainfall can cause different types of flooding, with flash floods being the most dangerous. They are difficult to predict, occur over a short period and can cause human casualties in addition to material damages.

The mechanism of increased heavy rainfall in the future climate is discussed in *Trenberth* (2011). It is mentioned that the water holding capacity of air increases with warming of the atmosphere. This leads to an increase in water vapor. As a result, storms, whether or not separate thunderstorms, cause more intense rainfall. An increase in the number of intense precipitations is even observed when the total amount of precipitation decreases (*Myhre et al.,* 2019). The increase in water content is considered to be the main reason for the increase in rainfall intensity in a number of studies, for example in *Dourte et al.* (2015). In areas with a general decrease in annual precipitation, the increase in the number of intensive precipitations is a consequence of the fact that the conditions for their occurrence become more likely in more months of the year. It is known that heavy rainfall prevails during the warm period of the year. Their character is mainly convective. In *Berg et al*. (2013) it is mentioned that in contrast, convective precipitation exhibited characteristic spatial and temporal scales, and its intensity in response to warming exceeded the Clausius – Clapeyron rate. It is concluded that convective precipitation reacts much more sensitively to rising temperatures than stratiform precipitation, becoming dominant in extreme precipitation. It is also noted that the Clausius - Clapeyron relation describes the rate of change of saturation vapor pressure of approximately 7% for every 1 ºC rise in at typical surface temperatures, and thereby sets a scale for increases in precipitation extremes. A statistically significant connection with near-surface temperature changes at a rate of between 5.9% and 7.7% for every 1 K rise in temperature is mentioned in *Westra et al*. (2013). A clear meridional dependence is also noted. According to *Hawcroft et al*. (2018), an increase in the number of extra tropical cyclones is the mechanism leading to an increase in extreme rainfall in the Northern Hemisphere (Europe and North America).

The increase of convective precipitation which is greater than the decrease of stratiform precipitation is noted in *Chernokulsky et al.* (2019). The influence of mountains and topography on precipitation and their intensity has been reviewed by many authors. The mechanism of impact of the mountains is described in *Houze* (2012). The convective systems are affected by channeling of airflow. The stratiform regions of mesoscale convective systems are enhanced by upslope flow when they move over mountains. In *Kirshbaum et al*. (2018) it is concluded, that the larger-scale background flow, local evapotranspiration, and transport of moisture, as well as thermodynamic heterogeneities over the complex terrain, regulate moist instability. It is noted there that longstanding limitations in the quantitative understanding of related processes, including both convective preconditioning and initiation, must be overcome to improve the prediction of this convection, and its collective effects in weather and climate models. According to *Shi* and *Durran* (2016), the sensitivity of extreme precipitation to warming in the climate simulations is lower over the mountains than over the oceans and plains. On the contrary, in *Giorgi et al.* (2016), the summer precipitation was analyzed over the Alpine region in an ensemble of twenty-first-century projections with high-resolution (12 km) regional climate models. They found that the regional models simulate an increase in precipitation over the high Alpine elevations that is not present in the global simulations. That was associated with increased convective rainfall due to enhanced potential instability by high-elevation surface heating and moistening. It can be assumed that the reduction of convective rainfalls in mountainous areas is due to the used thresholds. In the mountains, there is an effect of forced convection that leads to an increase in precipitation. For these to be more intense, additional surface super-heating is required, which occurs in lowland areas but is probably not sufficient at temperatures that decrease with height. The presence of snow cover additionally reduces the conditions for deep convection. This prevents the mountainons areas from reaching accepted thresholds for rainfall intensity. Model resolution is also important for rainfall amounts.

This article uses the definitions given by the WMO (2016). It is noted that there were large variations in precipitation patterns throughout the world, and it was not possible to use a single definition of extreme precipitation event that was suitable for all regions. According to the definition it was recognized generally, that when a precipitation event was considered to be extreme, it related to one of the following two contexts: (1) it exceeded a certain threshold, i.e., a fixed threshold, that has a certain associated impact, or (2) it could be considered to be extreme due to its rarity, i.e., a percentile-based threshold or based on its return period. It is mentioned that for the percentile-based threshold, the rarity of occurrence tended to take the form of the upper 90th, 95th, and 99th percentile of precipitation and such percentile-based thresholds could be derived from statistical cumulative density functions generated from the observed data or some conceptual distributions for precipitation extremes (such as generalized extreme value, GEV). It is also noted that when considering the most extreme precipitation events, return period information on the extremely rare events (100 years or more) was important for many engineering applications.

The second approach, although theoretically more reasonable, leads to certain difficulties. The problems arising from different methods for extreme precipitation assessment are commented in *Schär et al.* (2016), *Turco et al.* (2017), *Fougeres et al.* (2015), *Luo et al*. (2017). These problems are primarily related to the low frequency of such events, both for the past period and for simulations for future periods. As mentioned in *Jeon et al*. (2016), there was a risk that bias correction could mask serious model errors in simulating the processes responsible for the extreme event in question. This risk was also present in more commonly-used bias correction techniques such as the use of anomalies based on subtracting off or dividing by a reference value.

The role of temperature in the sub-daily convective precipitations is discussed in *Park* and *Min* (2017). It is mentioned that they are more sensitive to temperature changes as a result of the statistical effect that involves the transition from stratiform to convective types and the physical effect by which the convective process itself can overcome the thermodynamic limitation of the Clausius–Clapeyron relationship. The existing problem with the sub-daily precipitation is mentioned in *Alexander* (2016). It is also noted that another issue for extremes was the general mismatching of the spatial scales between observations (usually taken at point locations) and climate model simulations (typically interpreted as representing an area of a model grid), making it difficult to conduct a like-with-like comparison between observations and models. In *Westra et al*. (2014) it is mentioned, that low-resolution models have limited ability to simulate sub-daily precipitation extremes, as they do not explicitly resolve convective processes. This casts strong doubts on future projections in sub-daily precipitation extremes. This could be possible only if models had convection-permitting resolutions. Similar remarks shared by other authors justify the method adopted here using daily precipitation. The aim is to find the appropriate definition of extreme rainfall that can be applied to any grid-point of the model integration area.

According to *IPCC* (2012), it is likely that there have been statistically significant increases in the number of heavy precipitation events in more regions than there have been statistically significant decreases, but there are strong regional and sub-regional variations in the trends. There is also high confidence that changes in heavy precipitation will affect landslides in some regions. It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will increase in the 21st century over many areas of the globe. The projected seasonal mean changes in temperature and heavy precipitation for three emission scenarios (A1B, RCP45, RCP85) over Europe are presented in *Jacob et al.* (2014). Projections show an increase in heavy precipitation in most parts of Europe in winter by up to 35% during the end of the century and an increase in the summer heavy precipitation, except Southern Europe. A greater annual mean atmosphere warming is shown in Southern Europe and towards the northeast. It is also shown that large parts of Eastern Europe and the Alpine region might be exposed to a temperature increase of more than 4.5 ºC by the end of the century. They also found that the high-resolution in the simulations is clearly visible in the change pattern for heavy precipitation events. The more detailed spatial patterns in the high-resolution simulations can be related to better resolved physical processes like convection and heavy precipitation.

According to the latest IPCC AR6 report (*IPCC*, 2021), the frequency and intensity of heavy precipitation events have likely increased at the global scale over a majority of land regions. Heavy precipitation has likely increased on the continental scale over Europe and will generally become more frequent and more intense with additional global warming. Human influence, in particular greenhouse gas emissions, is likely the main driver of the observed global scale intensification of heavy precipitation in land regions.

In *Vautard et al.* (2021), the performance of the large EURO-CORDEX ensemble was analyzed. This ensemble consisted of 55 simulations combining 8 global climate models (GCMs) and 11 regional climate models (RCMs). They focused on biases for the most important climate variables like temperature, precipitation, wind, radiation, sea level pressure, and a variety of extreme and impact oriented indices. They found that the simulations were overall too cold, too wet, and too windy compared to available observations or reanalyses. They have also found that the substantial model overestimation of heavy precipitation indices when assessed with E-OBS data could be reduced by resorting to high-resolution precipitation data sets, which had a denser station network, especially in topographically complex regions.

A companion paper (*Coppola et al*., 2021) was providing an analysis of future projections, including comparison between EURO-CORDEX, CMIP5, and CMIP6 ensembles. This paper analyzed the ensemble of regional climate model projections for Europe completed within the EURO-CORDEX project. Projections were available for the two greenhouse gas concentration scenarios RCP2.6 (22 members) and RCP8.5 (55 members) at 0.11 degree resolution from 11 RCMs driven by 8 GCMs. They concluded that the maximum warming was projected by all ensembles in Northern Europe in winter, along with a maximum precipitation increase there; in summer, maximum warming occurred in the Mediterranean and Southern European regions associated with a maximum precipitation decrease. For the mean European climate, the south-north seasonal gradients in temperature and precipitation change signals were projected, with maximum warming and increase in precipitation over the northern regions in winter and maximum warming and a significant decrease in precipitation over the southern regions in summer, and in particular over the Mediterranean basin.

Recently, ensembles of models are often used to assess possible climate change. This assessment is an estimate of uncertainty rather than the basis for any averaged and more reliable scenario, because different regional models with different resolutions and driving global models have different estimates of possible changes in the temperature and rainfalls. The regional model RegCM4 (*Giorgi et al*., 2012) was used in this work. The systematic errors in the previous version RegCM3 have been investigated in *Bergant et al.* (2007). The model shows a cold averaged bias over Europe with the exception of the northern part between −1.2 °C and +1.0 °C. It also shows a prevailing wet averaged bias. The distinction between coastal and inland regions can also be seen. An overview and analysis of newer versions of the regional models involved in the Med-CORDEX simulation can be seen in *Somot et al.* (2018). The Med-CORDEX domain includes the Mediterranean climate zone, the Mediterranean Sea, and the river catchment basins of the Mediterranean and Black Seas. As mentioned, many factors like strong land-sea contrast, ground-atmosphere feedback, intensive air-sea connection and aerosol-radiation interaction, as well as a variety of regional characteristics must be taken into account when modeling the

Mediterranean climate. In this study, a smaller and climatically homogeneous area was selected compared to those used for Europe. It includes the Balkan Peninsula and part of the Apennine Peninsula. This is done on the assumption that the factors that determine climate change are more homogeneous. Thus, we can expect a more appropriate estimate of the change in the number of intense convective precipitation events.

2. Data and method

The aim of the article is to present a possible way of estimating the expected changes in heavy rainfall. The goal is not to compare different models or model modifications. The RegCM version 4.4.5 regional climate model (*Giorgi et al.*, 2012) forced with boundary conditions from HadGEM2-ES global climate model (Hadley Centre Global Environment Model - Earth-System version 2, (*Collins et al*., 2011) has been used. The RegCM4 originates from the regional climate model developed by *Giorgi et al.* (1993a, 1993b). RegCM4.4.5 has a dynamical core of the fifth-generation Mesoscale Model (MM5) from the National Center for Atmospheric Research (NCAR) and Pennsylvania State University (*Grell et al.,* 1994). The RegCM4 is a hydrostatic, compressible, sigma-p vertical coordinate model run on an Arakawa B-grid. It uses the radiation scheme of the Community Climate Model 3 (CCM3) (*Kiehl et al.,* 1996). Many studies on the validation and calibration of numerical models have been published lately (*Torma et al*., 2011; *Pieczka et al*., 2016; *Kotlarski et al*., 2014; *Giorgi et al*., 2012). In addition, numerical models depend on a set of initial variables and parameters, as they use a series of simplifications and parameterizations of natural processes. In this study, the Grell scheme (*Grell,* 1993) with the Arakawa – Schubert (*Arakawa* and *Schubert*, 1974) closure assumption (Grell-AS) was used for convective precipitation parametrization. A sensitivity analysis of five experiments with different convective precipitation schemes found that the model sensitivities of extreme precipitation to global warming are lower over mountains than over oceans and plains sensible to the choice of cumulus convection scheme, and that the most appropriate convective precipitation scheme in the region covering Bulgaria is the Grell scheme with Arakawa-Schubert closure (*Valcheva* and *Peneva*, 2014). For large-scale non-convective precipitation, the sub-grid explicit moisture scheme (SUBEX) (*Pal et al*., 2000) was used. The second-generation biosphere–atmosphere transfer scheme (BATS) (*Dickinson et al*., 1993) was used for simulating land surface processes. Sensitivity experiments of RegCM4 to planetary boundary layer parameterization were done by *Güttler et al*. (2014), where the planetary boundary layer modeled on the basis of the modified scheme of *Holtslag et al*. (1990) is used. More details on the model can be found in *Elguindi et al*. (2014). The model employs 18 vertical sigma levels, with a model top at 25 hPa and a bottom at 995 hPa. A simulation domain covering the Balkan Peninsula and part of the Apennine Peninsula is presented using Lambert conformal projection suitable for mid-latitudes (*Fig. 1*). The domain was centered at 24 E - 42 N, with a grid size of 20 km and 128×96 grid points, which correspond to 2560×1920 km^2. These spatial resolution leads to a time step of 60 seconds according to Courant - Friedrichs - Lewy criterion. The results are shown after removing the buffer zone from 12 grid points from each side of the domain. RCP scenarios were used in this study (*Moss et al.*, 2010). The experiments were according to the RCP4.5 (*Thomson et al.*, 2011) and RCP8.5 (*Riahi et al.,* 2011) scenarios. The reference period is from 1975 to 2004. The future periods are from 2021 to 2050 and from 2071 to 2099.

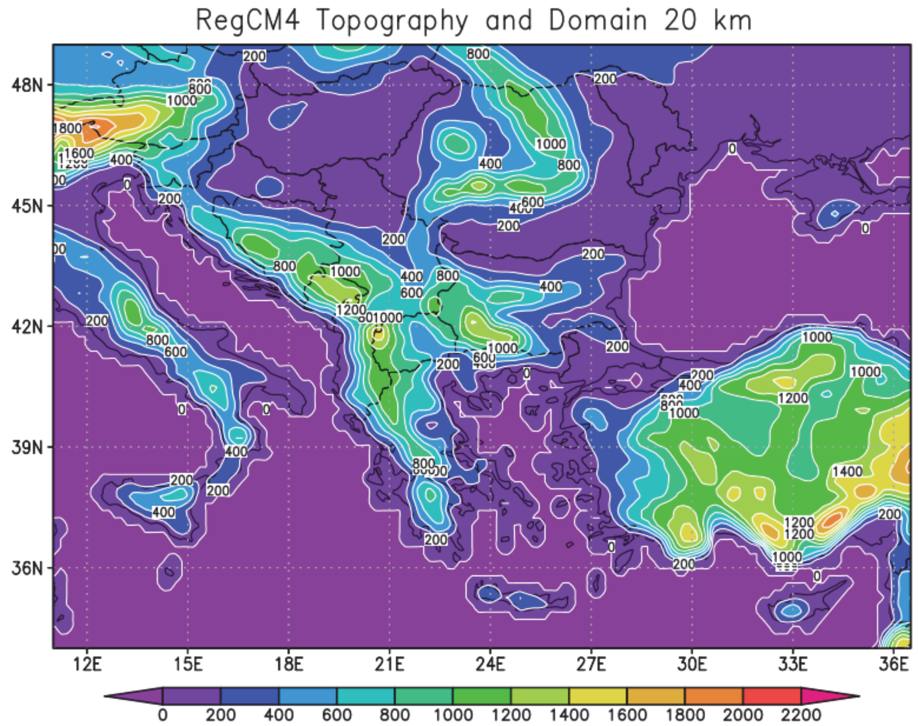

Fig. 1. Regional climate model topography (m) and domain size after removing the buffer zone.

The greenhouse gas concentrations in the RCPs closely correspond to the emission trends discussed in *Clarke et al*. (2010). RCP2.6 has a peak in carbon dioxide concentrations around 2050, followed by a modest decline to about 400 ppm, by the end of the century. RCP6 and RCP4.5 show a stabilizing carbon dioxide concentration, close to the median range in the literature. For CO_2, RCP8.5 follows the upper range, rapidly increasing carbon dioxide concentrations (*van Vuuren et al*., 2011). The hypothesis accepted here is that the increase in greenhouse gases is the reason for the increase in the number of extreme rainfall. This is why we use RCP4.5 (stabilizing concentration) and RCP8.5 (increasing concentration) scenarios for this study.

The climate models make it possible to estimate rainfall intensities for sub-daily internals. As noted, such intervals have drawbacks, also because the shorter the time interval for determining the intensity, the greater the error will be in the extrapolation in the grid points of the model. Together with the circumstances mentioned in Section 1 for sub-daily intervals, this is the reason for estimating the changes in the number of heavy rains over a period of 24 hours.

The thresholds used by Meteoalarm (http://www.meteoalarm.org/) provide such an opportunity. Each country participating in this network has set thresholds for dangerous weather, and in particular for heavy rainfall. The threshold for heavy rainfall depends on both on the climatic norms typical for the country and on the infrastructure. The color scale is

- yellow: the weather is potentially dangerous;
- orange: the weather is dangerous;
- red: the weather is very dangerous.

The infrastructure is taken into account insofar as the purpose of this system is to warn people travelling in Europe of severe weather. This can lead to inhomogeneity in setting the thresholds for heavy rainfall. For example, two areas with the same climate may have different protection facilities. In this case, the warning thresholds may differ. In the region under consideration, the countries falling within it have very close thresholds, as can be seen from the study in the RAIN project.

Following point 1 of the WMO guidelines noted above, fixed thresholds will be examined. An important step is the choice of thresholds for intense (actually 'dangerous' rainfall). In order for the simulations to be relevant, the cases should not be too small. Their number decreases sharply with increasing threshold. Therefore, the accepted values for the ‘yellow’ code in the countries of the district will be used as a measure to change the hazardous precipitation. The threshold amounts are for the 24-hour precipitation. They with the respective threshold values accepted in them are: Bulgaria (15), Croatia (25), Hungary (20), Italy (20), Romania (25), Serbia (30), and Slovenia (20).

These thresholds are also used to determine the risk of floods. Floods depend on many factors, such as basin size, slope, land cover, soil type, etc. These are specific for each catchment and must be taken into account separately when assessing flood risk. Despite the local specific conditions, in *Hurford et al.* (2012) the average 24-hour rainfall leading to floods varies from 20 mm to 45 mm with an average value of about 35 mm.

The expression ‘rare event rule’ (*Taylor*, 2021) is accepted in the statistics: ‘If specifically observed event is extremely rare, then the assumption is probably incorrect’. Two series of events are usually compared:

– an event that easily occurs,
– an event that is highly unlikely to occur.

Here, only the accepted thresholds are compared, without statistical analysis and use of confidence intervals. It is assumed that a detailed statistical analysis with even more observations was performed everywhere before determining the hazard categories.

The E-OBS observational database, version 23.1e (*Cornes et al.*, 2018) is available on a 0.1 and 0.25 degree regular grid. In this study, E-OBS v.23.1e daily precipitation sum above the mentioned threshold were used on 0.25 regular grid, for the period 1975–2004. From *Fig. 1* it is seen, that the cases with precipitation of 30 mm/24h are missing in large areas of the considered domain (including Bulgaria). Increasing the threshold will lead to fewer events and a breach of the rare event rule. In these areas, the ‘yellow code’ thresholds for the country concerned guarantee the existence of an acceptable number of cases (e.g., over 15), but this is not the case for the 'orange code' thresholds.

3. Results and discussions

In *Figs. 2* and *3* we compare the annual number of cases when precipitation is greater than or equal to 15, 20, 25, and 30 mm/24h from observations (*Fig. 2*) and simulations (*Fig. 3*). Firstly, we prepare daily precipitation sum from RegCM precipitation data, after that we count the cases with precipitation above the mentioned thresholds, and finally the result is divided by the number of years (30 or 28, depending on the period) to get annual (seasonal) number of cases (*Fig. 3*). The same procedure is applied for E-OBS precipitation data (*Fig. 2*) in order to compare simulated data with observational data. As we can see, RegCM4 overestimates the annual number of cases above all the thresholds, especially over the Carpathian Mountains, the eastern coast of Adriatic, Ionian and Aegean Seas.

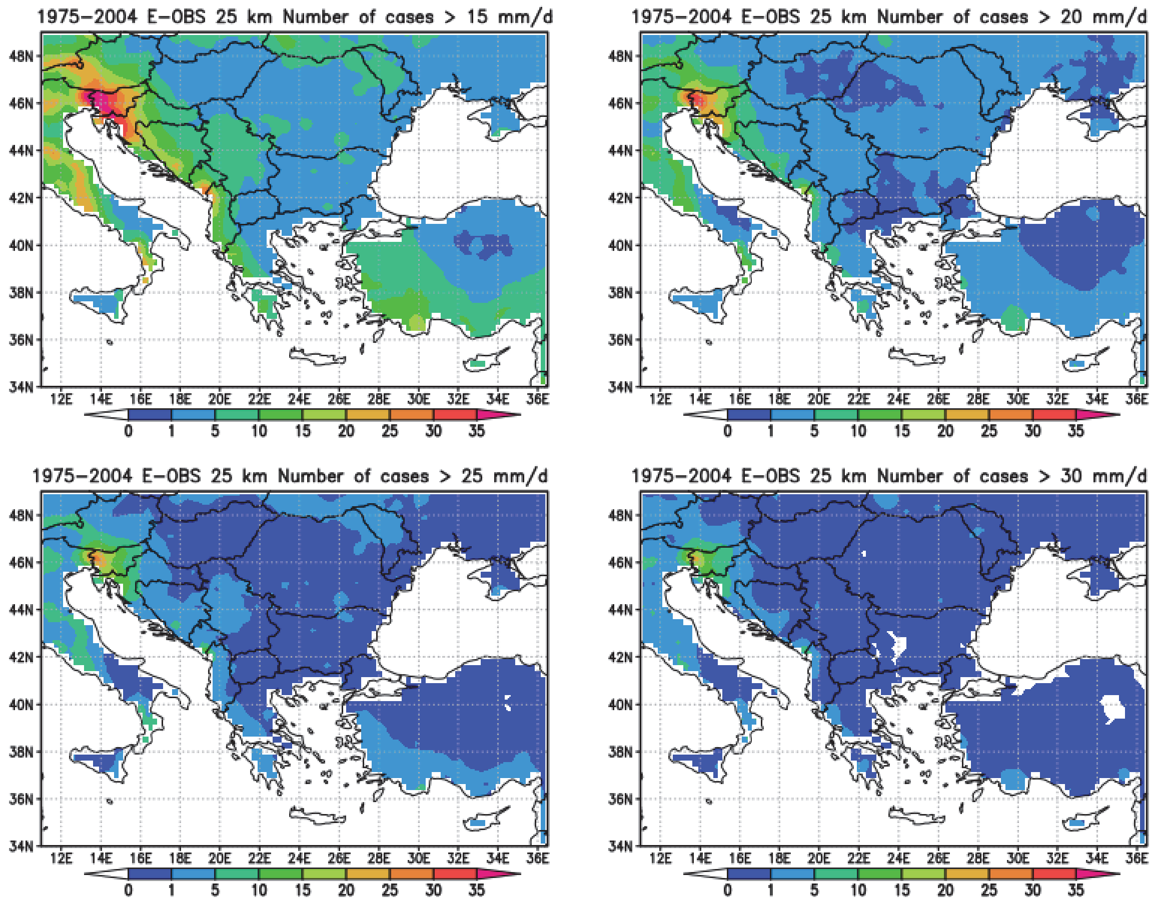

Fig. 2. Annual number of cases when precipitation >= 15, 20, 25, and 30 mm/24h according to the E-OBS precipitation data with 0.25º x 0.25º resolution for the period 1975–2004.

In *Spiridonov* and *Balabanova* (2021), the conclusion is made that the number of cases with convective precipitation over 35 mm / day is preserved during the year, although it decreases in the summer. The reason is the increase in temperature during the other seasons, which creates conditions for the development of convective precipitation. These values are in the 'orange' area of the indicated countries. The experiments were performed using the RCM ALADIN model according to scenario A1B. The consequence of this is that above this threshold, the number of heavy rains will not differ from that for the reference period. The difference is only in their distribution during the year. With warming, the conditions for these precipitation events are available over a larger period of the year, thus compensating the reduction in their number in summer (shown in the article below).

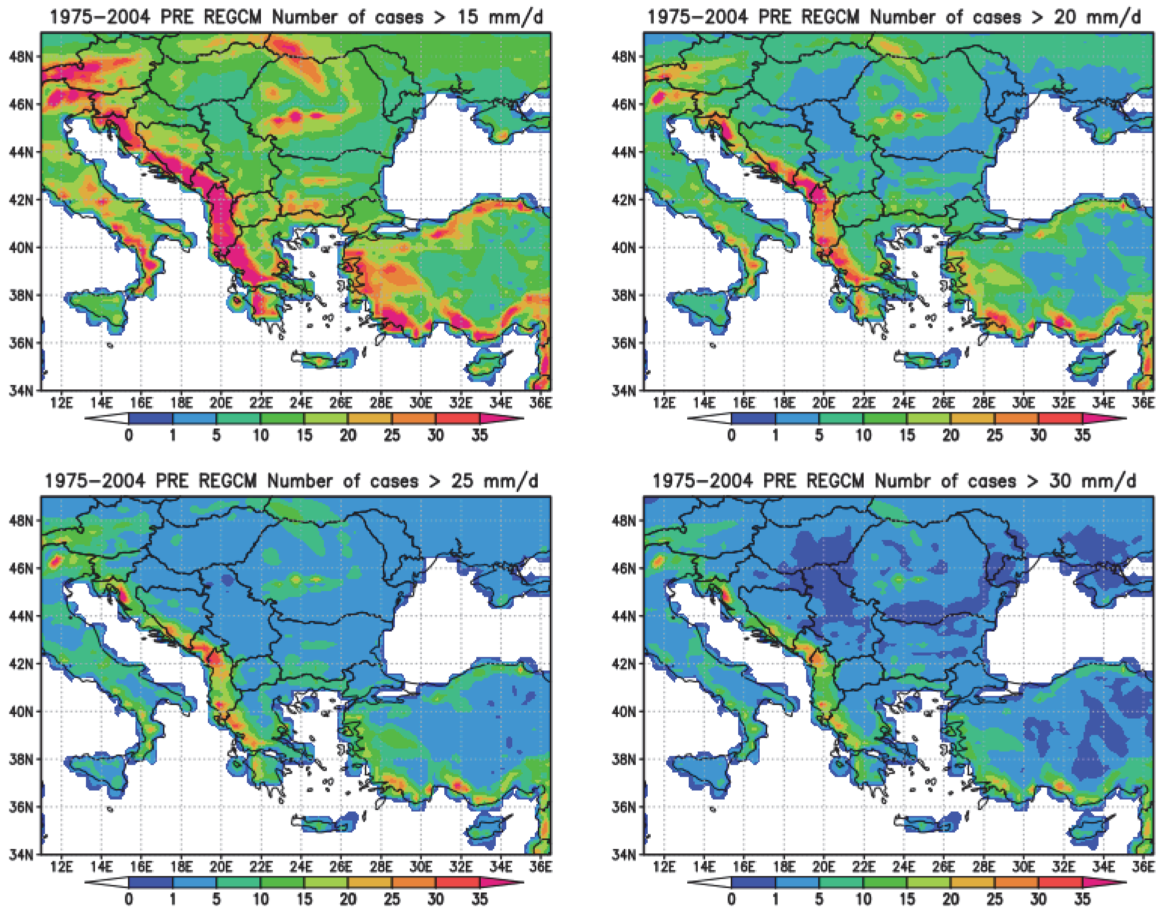

Fig. 3. Annual number of cases when precipitation >= 15, 20, 25, and 30 mm/24h according to the RegCM4 precipitation data with 20 km resolution for the period 1975–2004.

It is noteworthy that the areas with increasing and decreasing number of cases are different for the different intervals of intense rainfall. This may be due to the different effect of temperature conditions for the period under consideration as well as other local conditions. It is possible that the increase in precipitation in one interval is at the expense of their decrease in the other. This problem must be considered on its own.

In *Fig. 4,* simulated annual and seasonal mean changes in temperature in ºC are shown according to the RCP4.5 and RCP8.5 scenarios for the periods 2021–2050 and 2071–2099 compared with the reference period 1975–2004. Warming is observed throughout the year, especially during the summer season.

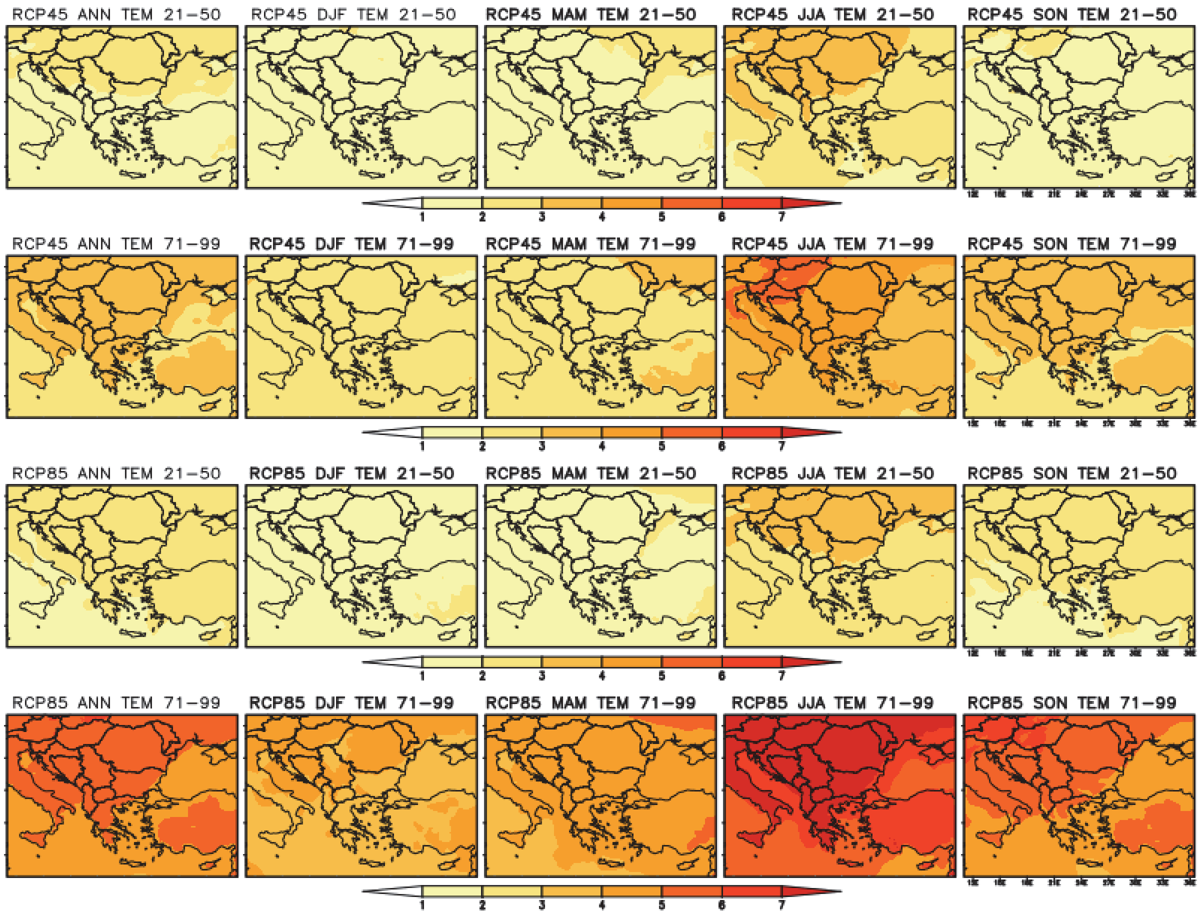

Fig. 4. Simulated annual and seasonal mean changes in temperature (in °C) with the regional climate model RegCM4-for the periods 2021-2050 and 2071-2099 according to the RCP4.5 (first two rows) and RCP8.5 (last two rows) scenarios compared with the reference period 1975–2004.

According to the RCP4.5 scenario, the annual temperature increase is between 1.5 ºC and 2.3 ºC in the first period and up to 3.5 ºC in the second period for the whole study area. During the first period 2021–2050, the greatest warming can be expected during the summer season between 2.5 ºC and 3 ºC. During the other seasons, the temperature rise is smaller, between 1.5 ºC and 2 ºC. During the second period 2071–2099, the temperature rises between 2 ºC and 2.5 ºC in the winter season and between 2.5 ºC and 3.5 ºC in spring and autumn. The temperature increase in summer can reach 5 ºC in the northern and northwestern parts of the region. According to the RCP8.5 scenario, the annual temperature increase is between 1.8 °C and 2.5 °C in the first period and between 4.2 °C and 5.8 °C in the second period for the whole region. During the first period 2021–2050, the greatest warming can be expected during the summer season between 2.5 °C and 3.5 °C. During the other seasons, the temperature rise is smaller, between 1.5 °C and 2.5 °C. During the second period

2071–2099, the temperature rise is between 3.5 °C and 4 °C in winter and spring and between 4.5 °C and 5.5 °C in autumn. The temperature increase in summer can reach 5–7 °C.

The simulations for convective precipitation above the used 24-hour thresholds are shown in *Figs. 5, 6, 7,* and *8*. They present changes between the future and the reference number of convective precipitation above the accepted threshold averaged per year (season).

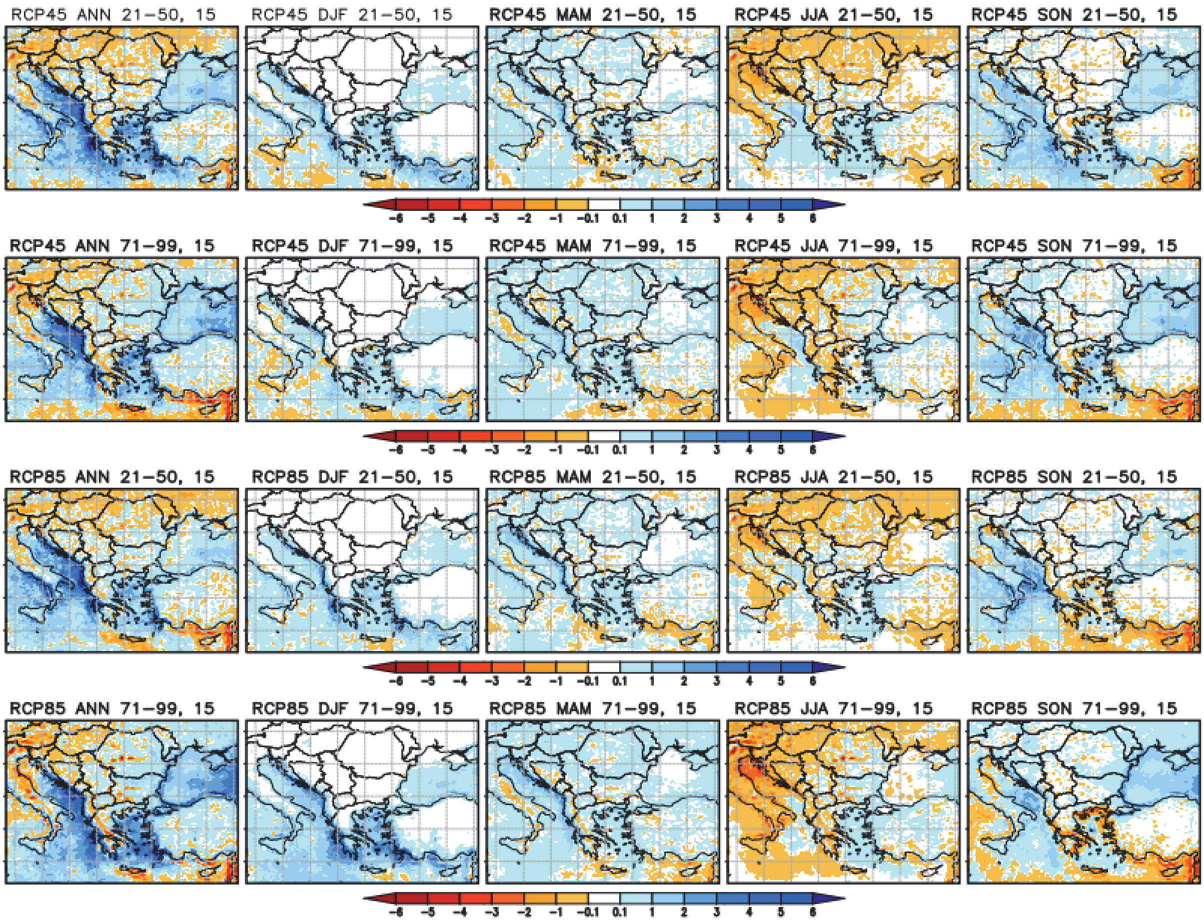

Fig. 5. Simulated annual and seasonal changes in the number of cases with 24-hour convective precipitation above the fixed threshold from 15 mm/24h averaged per a year (season) with the regional climate model RegCM4 for the periods 2021-2050 and 2071–2099 according to the RCP4.5 (first two rows) and RCP8.5 (last two rows) scenarios compared with the reference period 1975–2004.

Fig. 5 shows the annual and seasonal change in the number of cases with 24-hour convective precipitation above the threshold from 15 mm/24h averaged per year (season) for the periods 2021–2050 and 2071–2099 according to the

RCP4.5 and RCP8.5 scenarios compared with the reference period 1975–2004. The first column shows an increase in the number of cases of annual heavy convective precipitation along the eastern coasts of the Adriatic, Ionian, and Aegean Seas with 4–6 cases per year for both periods and for both scenarios and an increase with 1–2 cases over the half part of the continental areas. According to the RCP8.5 scenario, extreme rainfall can be expected to increase along the western coast of the Black Sea and also the Marmara Sea with 2–4 cases per years by the end of the century. A decrease in the number of cases of annual heavy convective rainfall can be expected in mountainous areas, especially in the eastern parts of the Alps, nevertheless the area holds the maximum precipitation total in the Alpine region according to the high-resolution observational precipitation dataset EURO4M (*Isotta et al*., 2014). The number of cases of annual heavy convective precipitation decreases in the Carpathians and the Balkan Mountains by 3–4 cases per year by the end of the century. When looking at the seasons, an increase in extreme rainfall is shown along the Adriatic and Aegean coasts in the winter season and along the eastern coast of the Adriatic Sea in autumn by 1–2 cases per season according to the RCP4.5 and by 2–3 cases for the period 2071–2099 according to the RCP8.5 scenario. There is no change in the number of extreme convective rainfall cases in winter season over the continental part of the studied area. A reduction in the number of extreme convective rainfall events in mountainous areas is shown during the summer season with 3–4 cases in the eastern parts of Alps and the Carpathians according to the RCP8.5 scenario by the end of the century. In the summer season, there is an increase in the number of extreme precipitation events in some parts of the coastal areas. In spring, there is an increase in the number of extreme convective events by 1–2 cases in almost the whole study area and an increase by 2–3 cases along the eastern Adriatic coast for the period 2071–2099 according to the RCP8.5 scenario. For Bulgaria according to the RCP8.5 scenario, extreme precipitation events in the Danube plain and the Dobrudzha plateau are expected to increase with 1–2 cases per year by the end of the century and along the Black Sea coast with 3 events per year. There is an increase in extreme convective precipitation events along the Black Sea coast in the autumn season by 1–2 events and along the Danube plain and the Dobrudzha plateau with 1–2 events per season. A decrease in extreme precipitation in mountainous regions is observed in the summer season with 3–4 cases per season, especially in the high parts of the Rila-Rhodope region and the Balkan mountain according to the RCP8.5 scenario for the period 2071–2099. According to the Meteoalarm program, this threshold corresponds to ‘yellow’ code in Bulgaria.

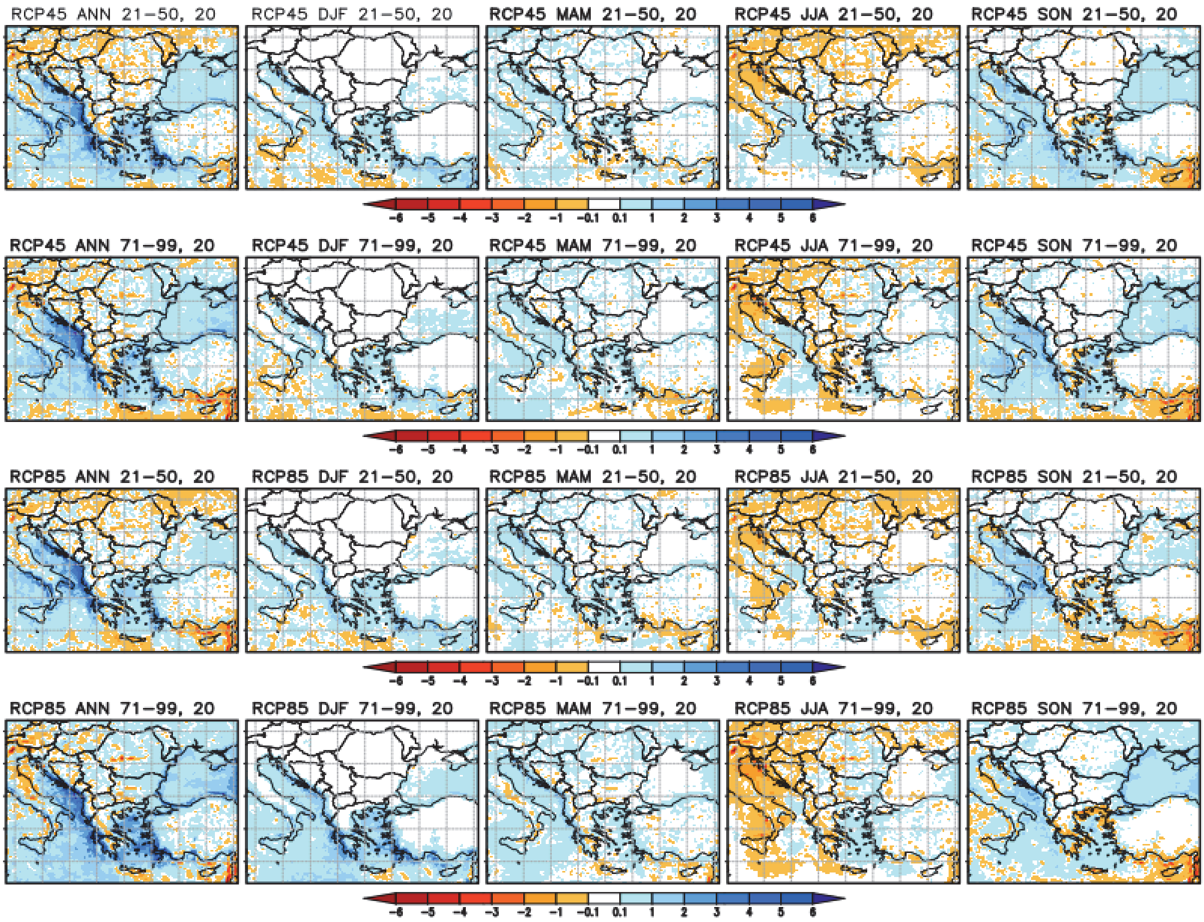

Fig. 6. Same as *Fig. 5*, but for the fixed threshold from 20 mm/24h.

Fig. 6 shows the annual and seasonal changes in the number of convective rainfall cases above the threshold of 20 mm/24h averaged per year (season). The first column shows an increase in the number of annual heavy precipitation events along the coasts of Adriatic, Ionian, and Aegean Seas with about 4–5 cases per year for both scenarios and both periods and Black Sea coast by 2–4 events according to RCP8.5 by the end of the century. In annual average, both RegCM simulations also depict an increase of extreme convective precipitation events over about half of the continental region, especially by the end of the century. There is a decrease in the number of annual heavy convective precipitation events in the continental parts of the studied area, especially over the mountainous regions (Carpathians, eastern parts of the Alps, Balkan Mountains, Rila-Rhodope region) by about 3–4 cases per year. When looking at the seasons, an increase in extreme rainfall is shown along the Adriatic and Aegean coasts in the winter season by 2–3 cases per season and along the eastern coast of the Adriatic Sea in autumn by 2–3 cases according to the RCP8.5 scenario by the end of the century. There is no change in the number of extreme convective precipitation events in winter over the continental part of the area. In spring, there is an increase in extreme rainfalls with 1–2 cases along the Adriatic coast. A decrease in the number of extreme convective rainfall events is shown in mountainous areas during the summer season with 3 cases per season, especially in the eastern parts of the Alps and the Carpathians. In summer, there is also an increase in the number of extreme precipitation events in some parts of the coastal areas by 1–2 cases. According to the Meteoalarm program, this threshold corresponds to 'yellow' code in Hungary, Italy, and Slovenia.

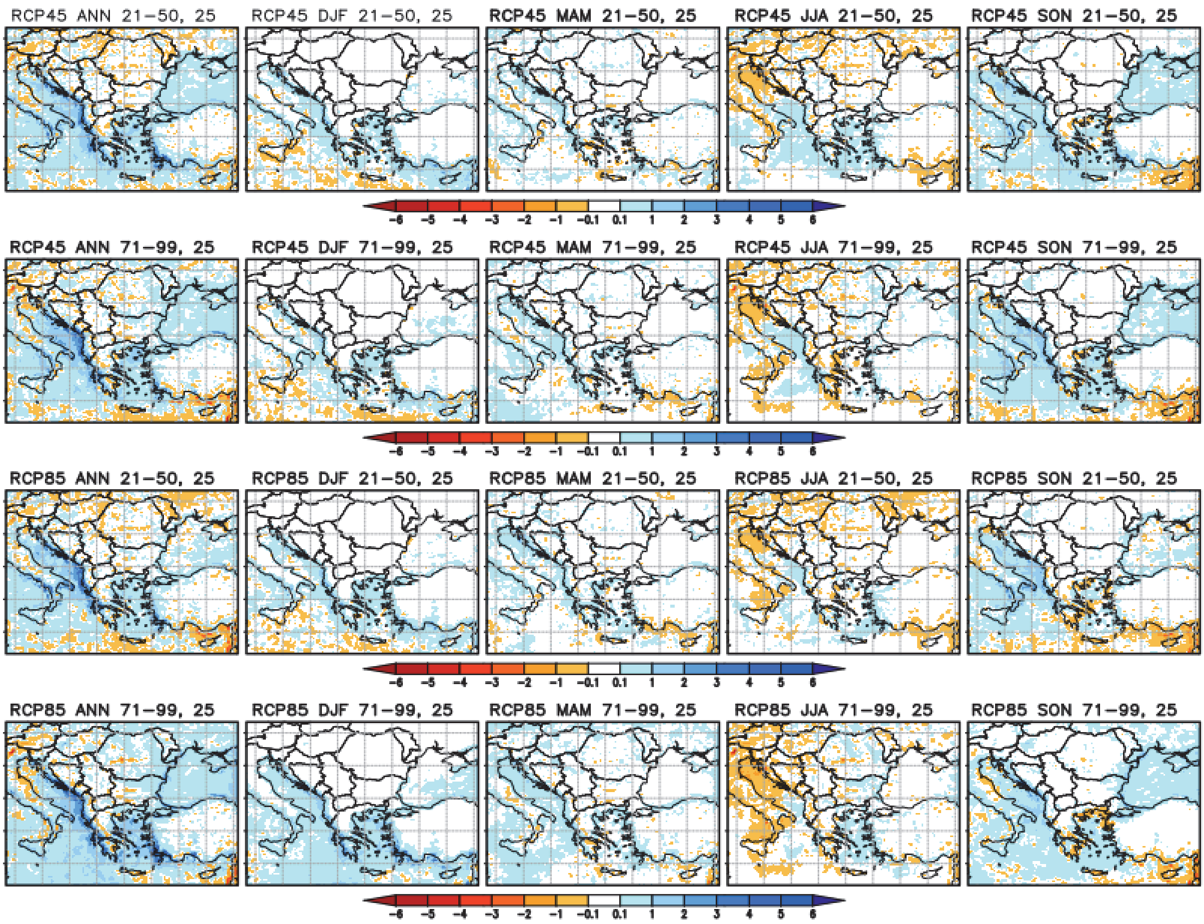

Fig. 7. Same as Fig. 5, but for the fixed threshold from 25 mm/24h.

Fig. 7 shows the annual and seasonal changes in the number of cases with 24-hour convective precipitation above the threshold from 25 mm/24h for the periods 2021–2050 and 2071–2099 according to the RCP4.5 and RCP8.5 scenarios compared with the reference period 1975–2004. Annual heavy precipitation events increase with 2–4 cases over the eastern coast of the Adriatic and Ionian Seas and western coast of Turkey. An increase in extreme rainfall cases is shown along the Adriatic and Aegean coasts in the winter season by 1–2 cases per season and along the eastern coast of the Adriatic Sea and over the Black Sea in autumn by 1–2 cases for both periods and both scenarios. There is no visible change in the number of extreme convective events in winter over the continental part of the area. In summer and spring, there is an increase in extreme rainfalls with 1–2 cases in some parts of the coastal areas. Again, we can expect a decrease in the extreme rainfall cases over the mountains areas on annual basis and a decrease over the continental parts during the summer season. According to the Meteoalarm program, this threshold corresponds to 'yellow' code in Romania and Croatia.

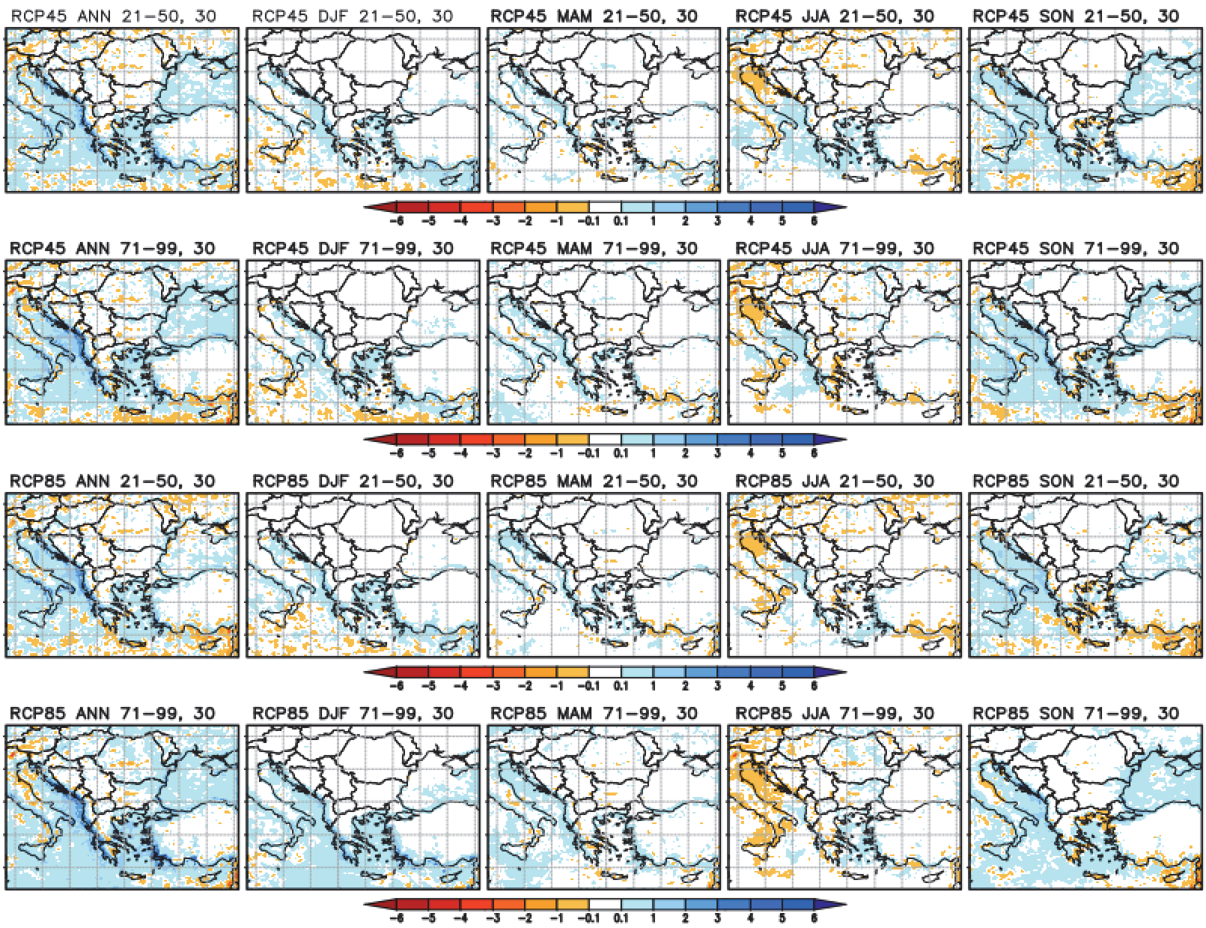

Fig. 8. Same as Fig. 5, but for the fixed threshold from 30 mm/24h.

Fig. 8 shows the annual and seasonal changes in the number of cases with 24-hour convective precipitation above the threshold from 30 mm per 24 hours averaged per year (season) for the periods 2021–2050 and 2071–2099 according to the RCP4.5 and RCP8.5 scenarios compared with the reference period 1975–2004. The first column shows an increase in the number of annual heavy convective rainfall cases along the coastline by 2–3 cases per year, especially along the eastern coast of the Adriatic Sea and the coast of Southern Italy, Greece, and Turkey for both scenarios and both periods. There is a decrease in the number of annual heavy rainfall cases in the mountainous areas by 1–2 cases per year. When considering the seasons, an increase in extreme rainfalls are expected in the autumn and winter seasons along the eastern coast of the Adriatic Sea by 1–2 cases for both periods and both scenarios. According to the Meteoalarm program, this threshold corresponds to ‘yellow’ code in Serbia.

For both periods of climate change simulation, in both scenarios the number of heavy convective rainfalls decreases in the mountainous areas. The corresponding increase in water content is not enough to increase the number of intense convective precipitation events. This effect is expressed mainly in the summer when the number of convective and / or stratiform precipitation decreases. The decrease in the number of cases of heavy rainfall does not exclude the increase in the amount of precipitation in these areas due to the increased water content according to the law of Clausius – Clapeyron. For that reason, *Fig. 9* shows the annual and seasonal changes in the amount of convective precipitation according to the RCP8.5 and RCP4.5 scenarios in percentages by the end of the century.

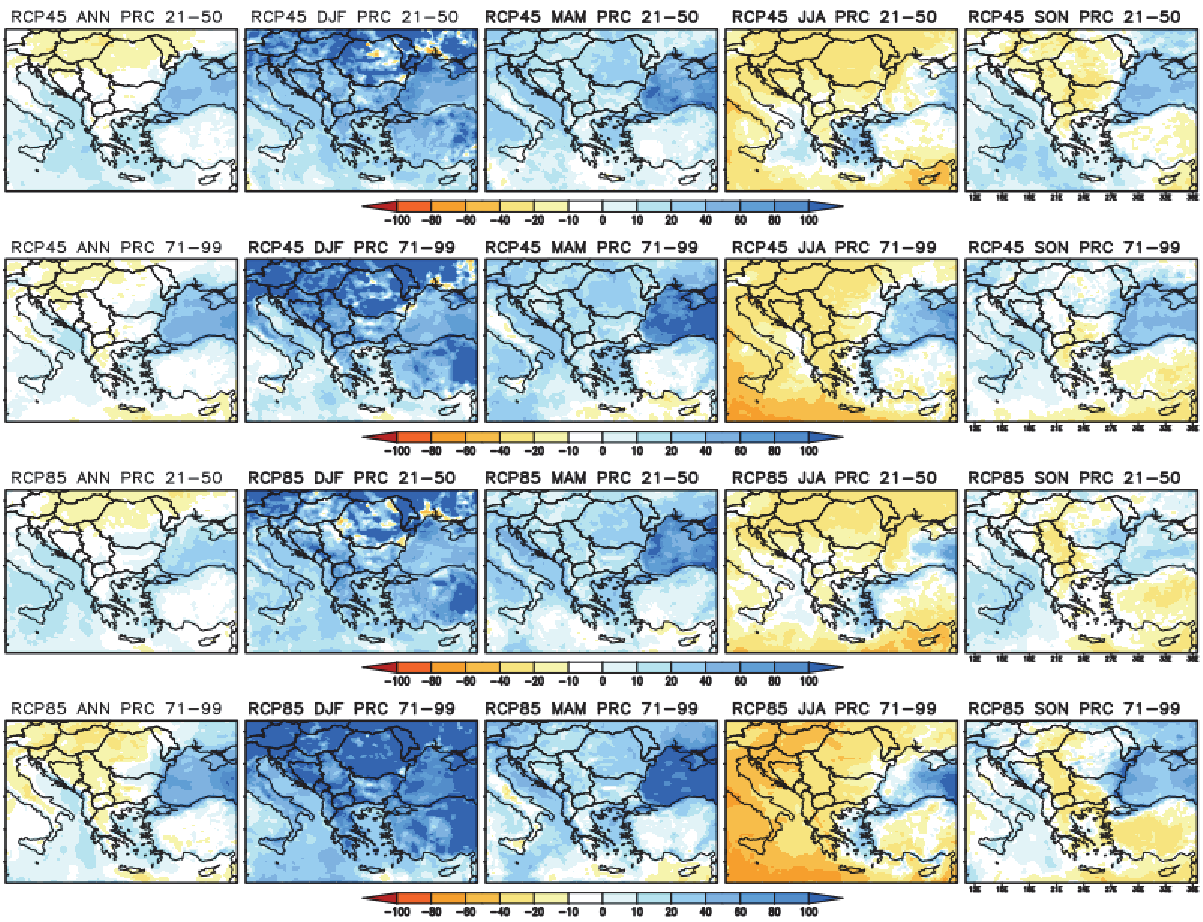

Fig. 9. Simulated annual and seasonal changes in the amount of convective precipitation (in %) with the regional climate model RegCM4 for the periods 2021–2050 and 2071–2099 according to the RCP4.5 (first two rows) and RCP8.5 (last two rows) scenarios compared with the reference period 1975–2004.

The first column of *Fig. 9* shows a decrease in the amount of the annual convective precipitation by 10–20% over the continental northwestern parts of the studied area and an increase in precipitation over seas, by 10–20% over the Adriatic and Aegean Seas, reaching 30–40% over the Black Sea. The most significant increase in convective rainfall is shown in the winter season according to the RCP8.5 scenario with almost 90% over the continental parts of the studied area for the both periods (2021–2050) and (2071–2099). Conversely, during the winter season there are no visible changes in the number of extreme rainfall cases above the 'yellow' code over the continental part of the domain (*Figs. 5, 6, 7,* and *8*). The amount of convective rainfall during the spring season also increases by 20–40% over the northern parts of the domain and especially over the Black Sea region by over 60%. During the summer season, the amount of precipitation decreases by 20–40% in almost the entire study area, except for the Aegean Sea and the eastern parts of the Black Sea. During the autumn season, there is a decrease in convective rainfall by 20–40% in the northwestern and southeastern continental parts of the region and an increase over the seas by 20–40%.

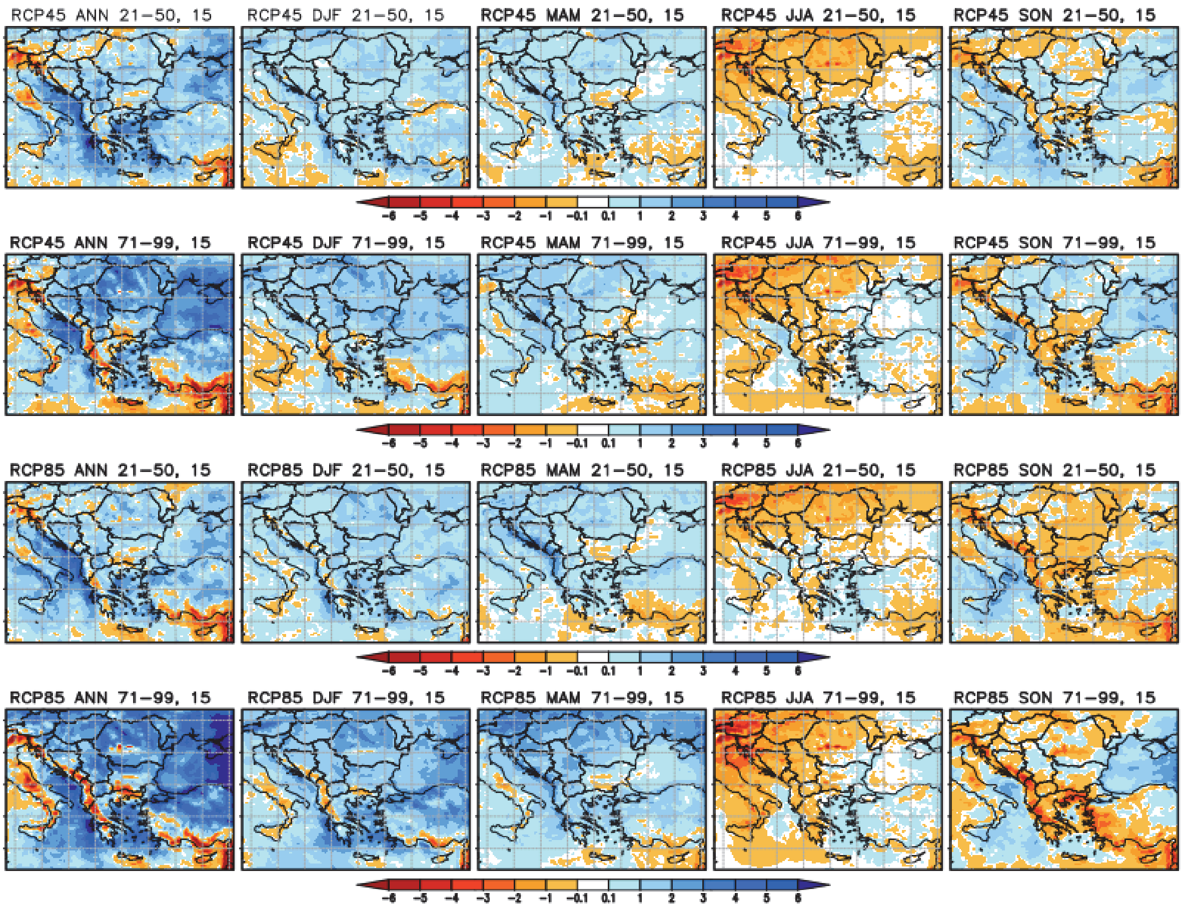

Fig. 10. Simulated annual and seasonal changes in the number of cases with 24-hour total precipitation above the fixed threshold from 15 mm/24h averaged per a year (season) with the regional climate model RegCM4 for the periods 2021–2050 and 2071–2099 according to the RCP4.5 (first two rows) and RCP8.5 (last two rows) scenarios compared with the reference period 1975–2004.

Due to the fact that the Meteoalarm thresholds are for total precipitation we have presented an additional information in *Figs. 10, 11, 12,* and *13* for the simulated annual (first columns) and seasonal (last four columns) changes in the number of cases with total precipitation above the fixed thresholds from 15, 20, 25, and 30 mm/24h, and also an information about the percentage (%) of the convective precipitation of total precipitation on *Fig. 14*.

Fig. 10 shows the simulated annual and seasonal changes in the number of cases with 24-hour total precipitation above the fixed threshold from 15 mm/24h for the periods 2021–2050 and 2071–2099 according to the RCP4.5 and RCP8.5 scenarios compared with the reference period 1975–2004 averaged per a year (season). The first column shows an increase in the number of extreme precipitation cases with 2–4 cases per year over the continental parts of the domain and in increase with 5–6 cases per year over the Adriatic, Ionian, Marmara, and Aegean Seas. There is an increase with 6–9 cases per year over the central part of the Black Sea by the end of the century. A decrease in the number of extreme rainfall can be expected over parts of eastern Alps, Dinaric, Pindus, Rila-Rhodope and Balkan Mountains, the southernmost parts of Turkey, and parts of Italy. When looking at the seasons there is an increase in extreme cases in winter and spring over almost the whole territory with 1–2 cases for both scenarios for the period 2021–2050 and 2–3 cases per season for the RCP8.5 scenario by the end of the century, a decrease in the summer season over the most parts of continental area of the studied domain, and an increase of extreme cases over half of domain in autumn. A reduction in the extreme rainfall is shown during the summer season with 4 to 6 cases, especially in the eastern parts of the Alps and the Carpathians according to the RCP8.5 scenario for the period 2071–2099, but also an increase in some parts of coastal areas.

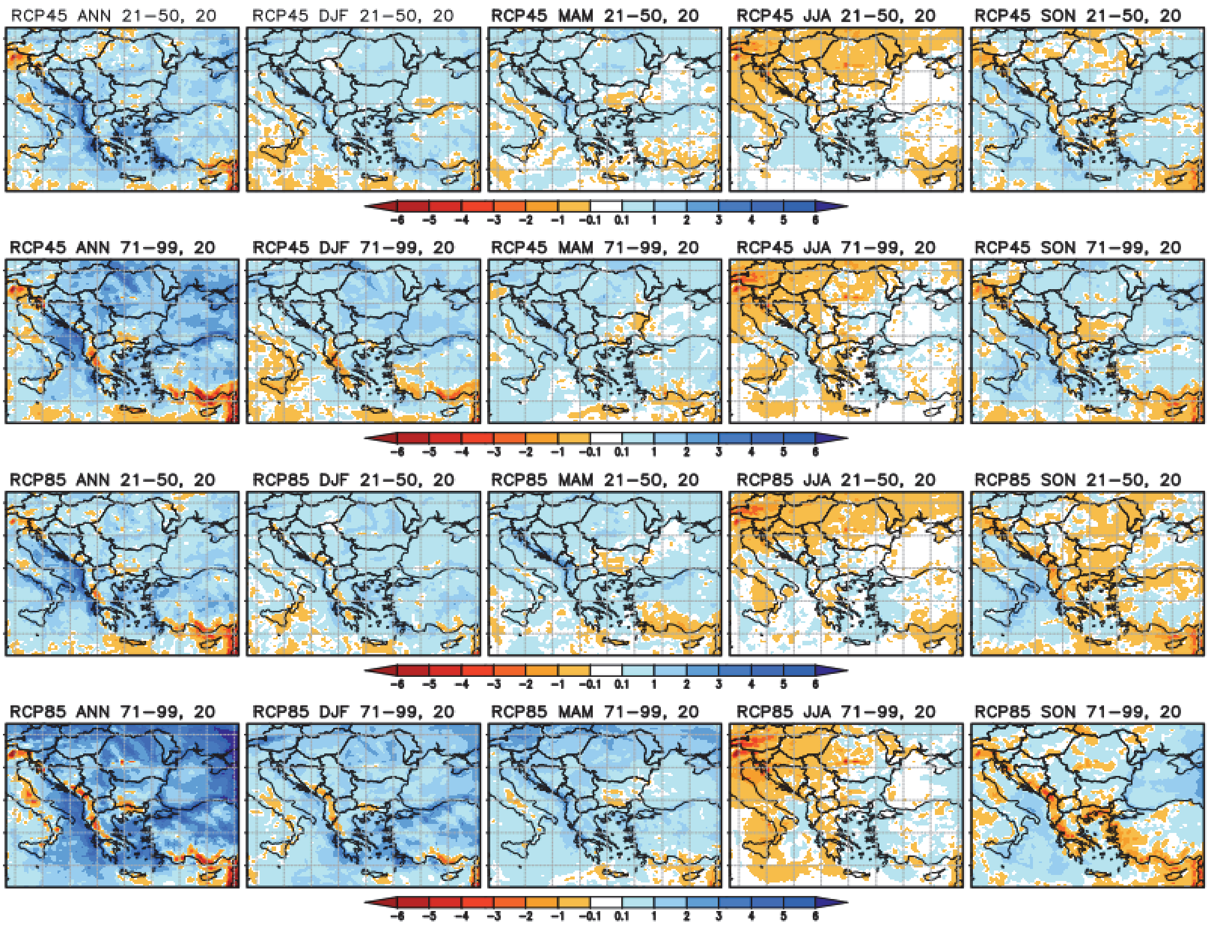

Fig. 11. Same as *Fig. 10*, but for the fixed threshold from 20 mm/24h.

Fig. 11 shows the simulated annual and seasonal changes in the number of cases with 24-hour total precipitation above the fixed threshold from 20 mm/24h averaged per a year (season) for the periods 2021–2050 and 2071–2099 according to the RCP4.5 (first two rows) and RCP8.5 (last two rows) scenarios compared with the reference period 1975–2004. The first column shows an increase in the number of annual heavy precipitation events over the continental parts of the studied area with 1–3 cases per year by 2050 and 4–5 cases by 2099, and an increase with 5–6 cases per year over the coastline according to both scenarios by the end of the century. A decrease in the number of extreme rainfalls is shown in the mountainons regions with 4–5 cases per year. In winter and spring an increase of extreme rainfall can be expected with 1–2 cases per season over most of the studied domain, an decrease in the number of extreme cases during the summer season, especially over the northern and northwestern parts of the domain, and in autumn over mountains areas.

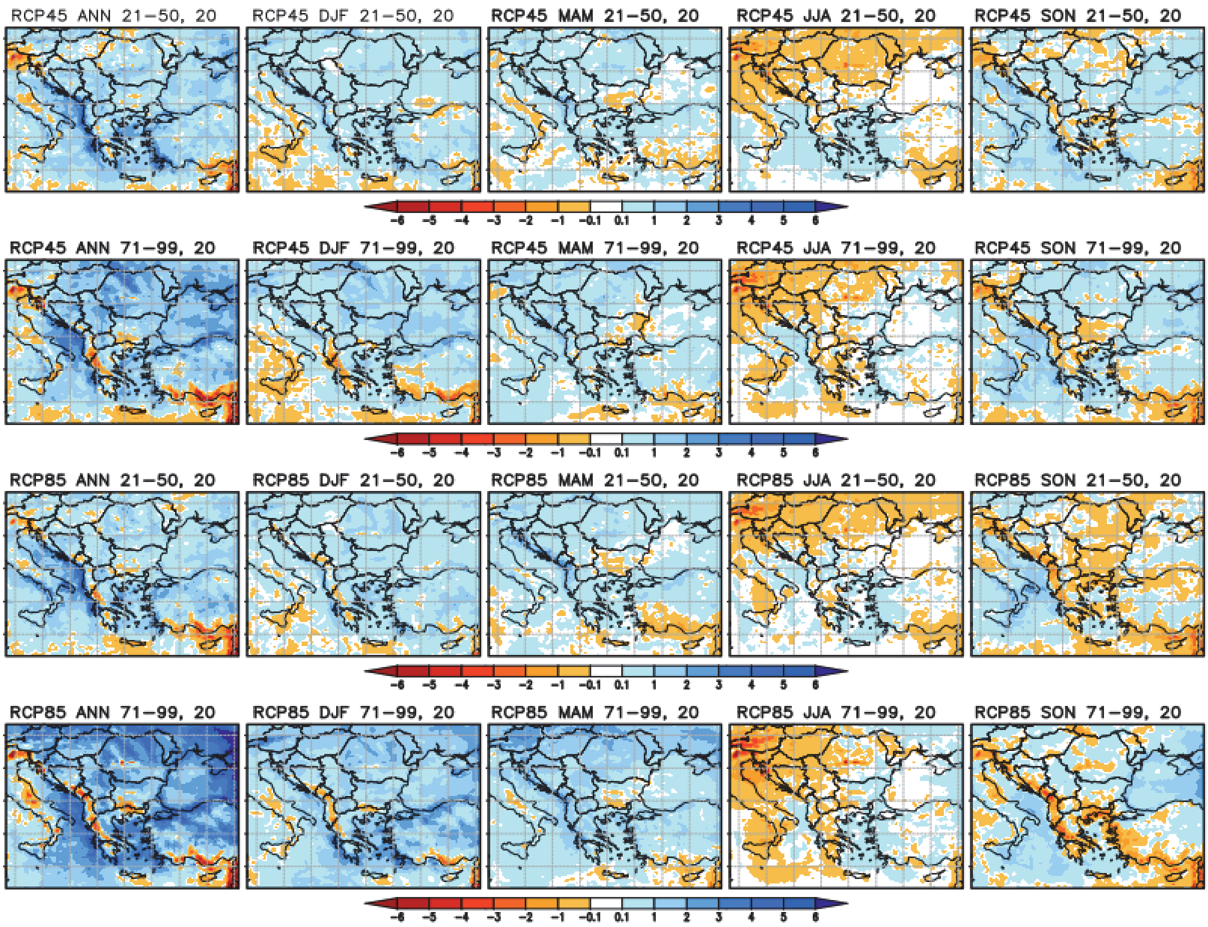

Fig. 12. Same as *Fig. 10*, but for the fixed threshold from 25 mm/24h.

Fig. 12 shows the annual and seasonal changes in the number of cases with 24-hour total precipitation above the threshold from 25 mm/24h for the periods 2021–2050 and 2071–2099 according to the RCP4.5 and RCP8.5 scenarios compared with the reference period 1975–2004. The annual heavy precipitation events increase with 2–4 cases over the continental parts and by 3–5 cases over the Aegean, Ionian, and the eastern coast of the Adriatic Seas. When looking at the seasons, there is an increase in the number of extreme rainfalls in winter and spring over almost the entire continental part of the domain, and a decrease in summer, especially over the northern and northwestern parts of the studied domain. In the autumn season, increase can be expected in the number of extreme rainfalls except in the mountains regions.

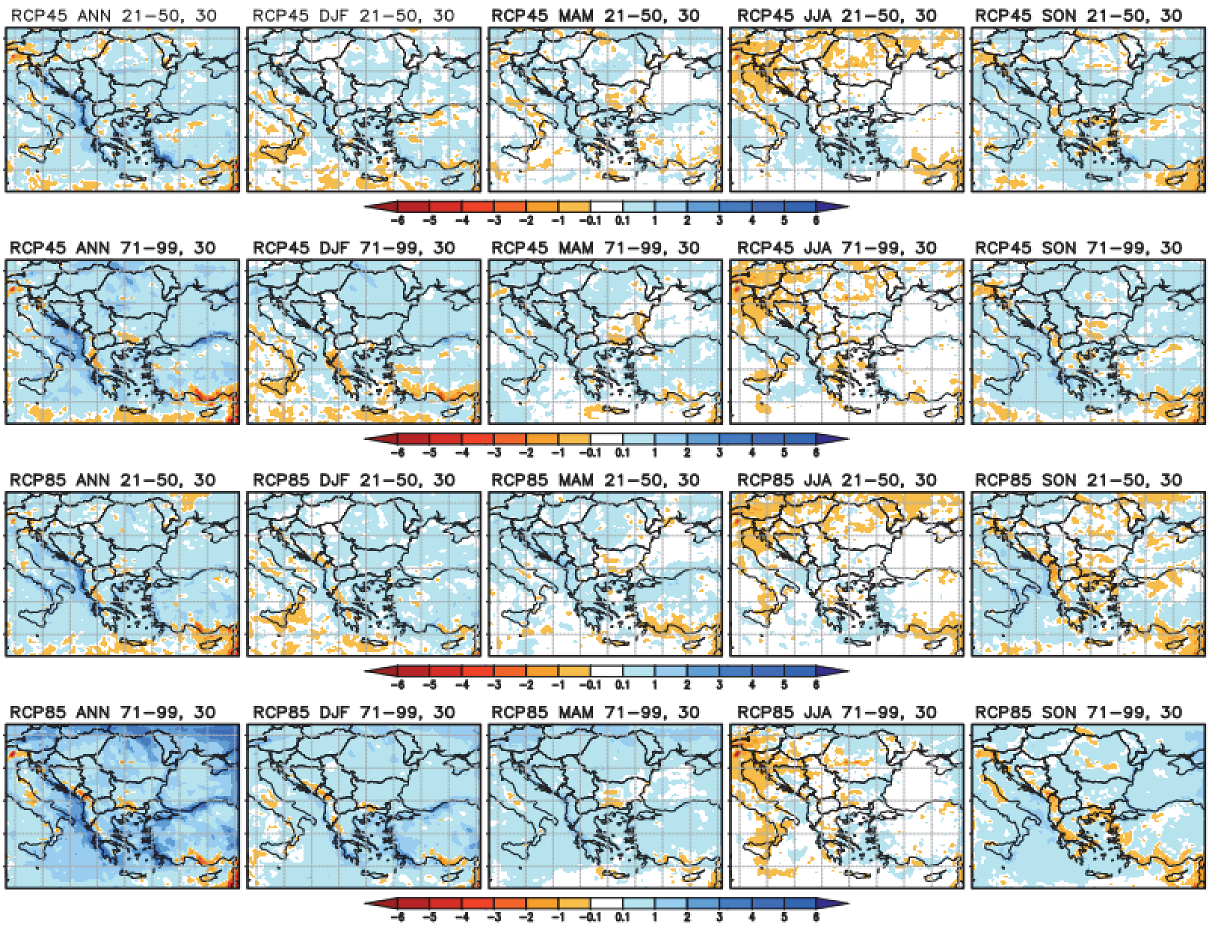

Fig. 13. Same as *Fig. 10*, but for the fixed threshold from 30 mm/24h.

Fig. 13 shows the annual and seasonal changes in the number of cases with 24-hour total precipitation above the threshold from 30 mm/24 hours averaged per year (season) for the periods 2021–2050 and 2071–2099 according to the RCP4.5 and RCP8.5 scenarios compared with the reference period 1975–2004. The first column shows an increase in the number of extreme events along the coastline with 2–3 cases per year, especially along the eastern coast of the Adriatic Sea and the coast of Southern Italy, Greece, and Turkey for both scenarios and both periods. An increase in extreme rainfalls is expected in the winter and spring seasons by 1–2 cases over most of the studied territory. A decrease in extreme rainfall is shown during the summer season in the northern and northwestern parts of the domain and an increase in the coastal areas.

The ratio of convective precipitation to total precipitation in the NCEP-NCAR analysis during the months of January, April, July, and October can be seen in *Myoung* and *Nielsen-Gammon* (2010). This ratio, obtained with the RegCM model by season is shown in *Fig. 14*.

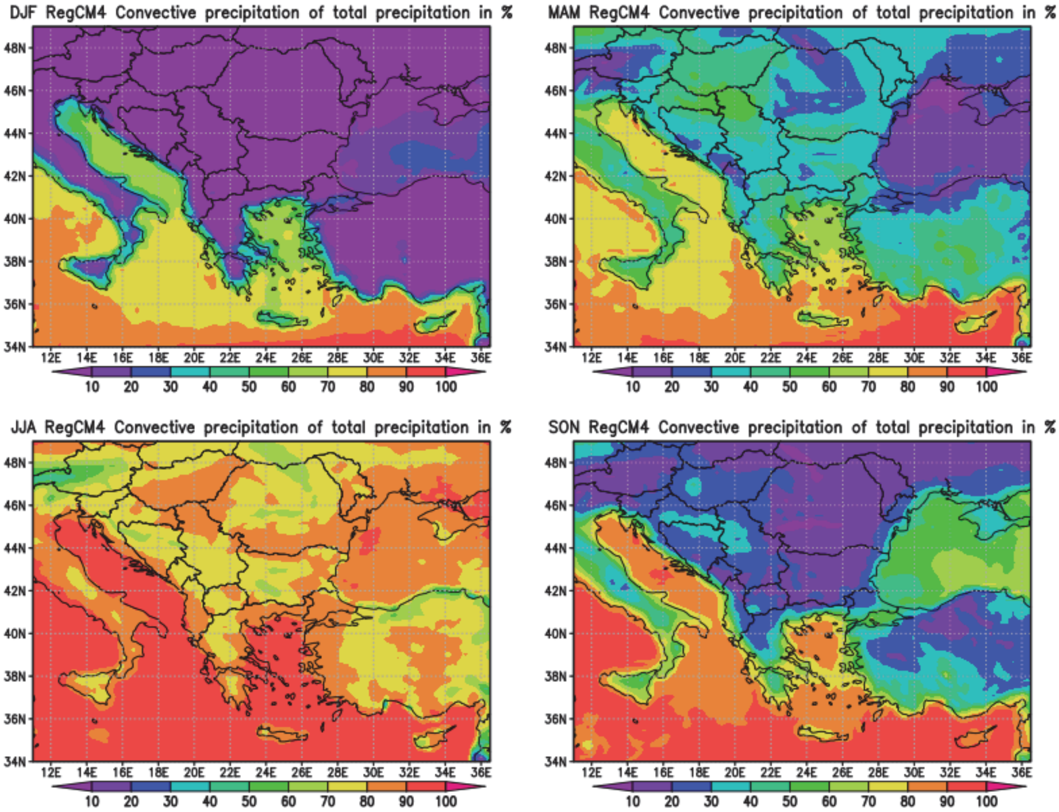

Fig. 14. Seasonal ratio of convective precipitation to total precipitation in % for the period 1975–2004.

Fig. 14 shows the seasonal ratio of convective precipitation to total precipitation in % for the period 1975–2004. In winter, the convective rainfall is 10% of the total rainfall over the continental part of the study area, with the exception of the coastal areas of the Adriatic, Ionian, and Aegean Seas, where the convective rainfall is about 20–50% of the total rainfall. In spring, the convective precipitation is 40–60% over the continental parts excluding mountains (20–30%) and 80–90% over the seas excluding the Black Sea (20–30%). In summer, 80–90% of the precipitation is convective except for the mountains (50–70%). In autumn, 10–30% of the precipitation is convective over the continental parts except over Italy and coastal areas (50–70%). In the annual rainfall (not shown here), between 80 and 90% of annual rainfall over the seas is convective except the Black Sea (between 30–50%). Over the continental parts of the domain, between 20 and 40% of the total precipitation is convective except the Adriatic, Ionian, and Aegean coasts (50–80%). For Bulgaria, according to the regional climate simulations, annual convective precipitation is 30–40% of the total precipitation for the whole territory: 40–50% for Hungary, 20–40% for Romania, 40–70% for Italy, 30–40% for Slovenia, 40–70% for Croatia, and 30–50% for Serbia.

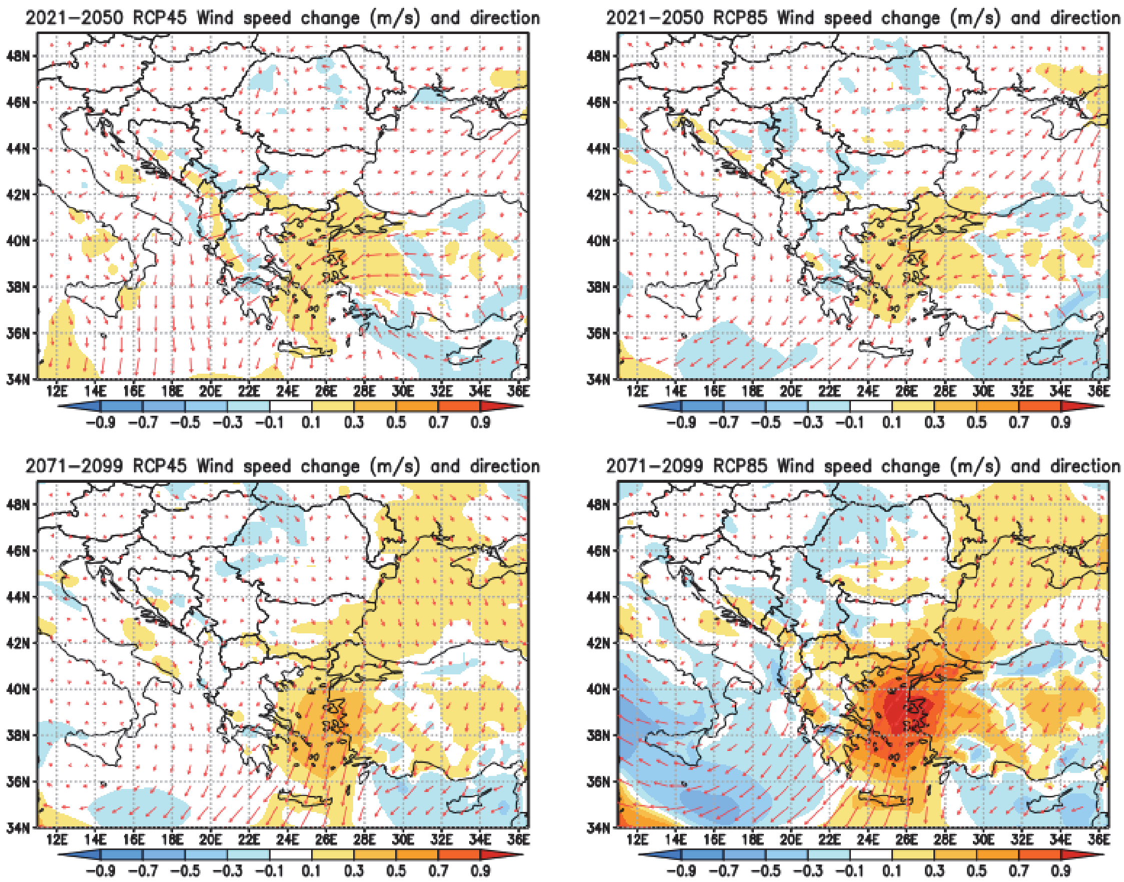

Fig. 15. Simulated annual mean changes of 10 m wind speed (m/s) and direction with the regional climate model RegCM4 for the periods 2021–2050 and 2071–2099 according to the RCP4.5 (first column) and RCP8.5 (second column) scenarios compared with the reference period 1975–2004. Wind direction and speed changes have been shown in vectors and shades, respectively.

Because of the strong increase of the extreme precipitation in the coastal area, we have also shown the simulated annual mean change of 10 m wind speed (m/s) and direction (*Fig. 15*) for the periods 2021–2050 and 2071–2099 according to the RCP4.5 (first column) and RCP8.5 (second column) scenarios compared with the reference period 1975–2004. The wind direction and speed change have been shown in vectors and shades, respectively. In the period 2021–2050, an increase in the annual wind speed of 10 m by 0.1–0.3 m/s is observed mainly in the coastal areas of the Aegean and Marmara Seas, parts of the eastern coast of the Adriatic Sea, and parts of western Turkey under both scenarios. In the period 2071–2099, an increase of 0.1–0.3 m/s is observed over the Black and Marmara Seas and by 0.3–0.5 m/s over the Aegean Sea under the RCP4.5 scenario. According to the RCP8.5 scenario, the increase is 0.3–0.5 m/s over the western Black Sea coast and parts of the eastern Adriatic coast, and 0.7–0.9 m/s over the Aegean and Marmara Seas.

4. Conclusions

The thresholds used by the Meteoalarm program were used as a measure of change in the hazardous precipitation over the studied domain. The accepted threshold values for ‘yellow’ code accepted in the countries from the district used in this study were: Bulgaria (15 mm/24h), Croatia (25 mm/24h), Hungary (20 mm/24h), Italy (20 mm/24h), Romania (25 mm/24h), Serbia (30 mm/24h), and Slovenia (20 mm/24h). Overall, it can be concluded that it is possible to identify areas with an increased risk of heavy rainfall using the Meteoalarm criteria.

According to the regional climate simulations with 20 km resolution, an increase in the number of hazardous total precipitation events can be expected in the coastal areas for both scenarios and for both periods, especially in the coastal areas of the Adriatic, Ionian, Aegean, Black, and Marmara Seas. In general, the number of extreme precipitation events can be expected to decrease over the mountains in this region on annual basis (eastern parts of the Alps, Carpathians, Dinaric Mountains, Pindus Mountains, Balkan Mountains, and Rila-Rhodopes Mountains). An increase in the number of dangerous precipitation cases can be expected in the winter and spring season, for all thresholds, an increase in the autumn season over the half continental part of the studied area, a decrease in summer season over the continental parts of the domain, and an increase in summer in some parts of the coastal areas.

Overall, the number of extreme convective precipitation cases above the accepted thresholds from 15, 20, 25, and 30 mm for 24-hour increase for both scenarios and both periods in the coastal areas and decrease over the mountains on annual basis. In the winter season, there is no change in the number of extreme convective rainfall cases over the continental part of the studied area. The reason for this is that simulations show that the winter convective precipitation is about 10% of the total precipitation in the continental parts of the study area. An increase in the extreme rainfall cases is shown along the Adriatic and Aegean coasts in the winter season and along the eastern coast of the Adriatic Sea in autumn for both periods, both scenarios, and all thresholds. In spring, there is an increase in the number of extreme convective events in almost the whole study area especially along the eastern Adriatic coast (cases above 15 and 20 mm/24h) and along the coastal areas (cases above 25 and 30 mm/24h). A reduction in the number of extreme convective rainfall events is shown in the mountainous areas during the summer season for all periods and all thresholds.

According to the regional climate simulations, between 20 and 40% of the annual precipitation is convective except for the Adriatic, Ionian, and Aegean coasts (50–80%). In the winter season, about 10% of the total rainfall is convective over the continental part of the studied area, with the exception of the coastal areas of the Adriatic, Ionian, and Aegean Seas, where the convective rainfall is about 20–50% of the total rainfall. In spring, 40–60% of the precipitation is convective over the continental parts excluding the mountainons regions (20–30%) and over the seas (80–90%) excluding the Black Sea (20–30%). In the summer season, about 80–90% of the precipitation is convective except for the mountains (50–70%). In autumn, 10–30% of the precipitation is convective over the continental parts except for Italy and coastal areas (50–70%).

Because of the strong increase of extreme precipitation in the coastal area, we have also presented spatial maps of the simulated annual mean change of the 10 m wind. An increase in the annual wind speed can be expected by 0.1–0.3 m/s, mainly over the coastal areas for the period 2021–2050 for both scenarios and by 0.3–0.5 m/s for the period 2071–2099 under the RCP4.5 scenario. According to the RCP8.5 scenario, an increase can be expected by 0.3–0.5 m/s over the western coast of the Black Sea, parts of the eastern coast of the Adriatic Sea, and by 0.7–0.9 m/s over the Aegean and Marmara Seas for the period 2071–2099.

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