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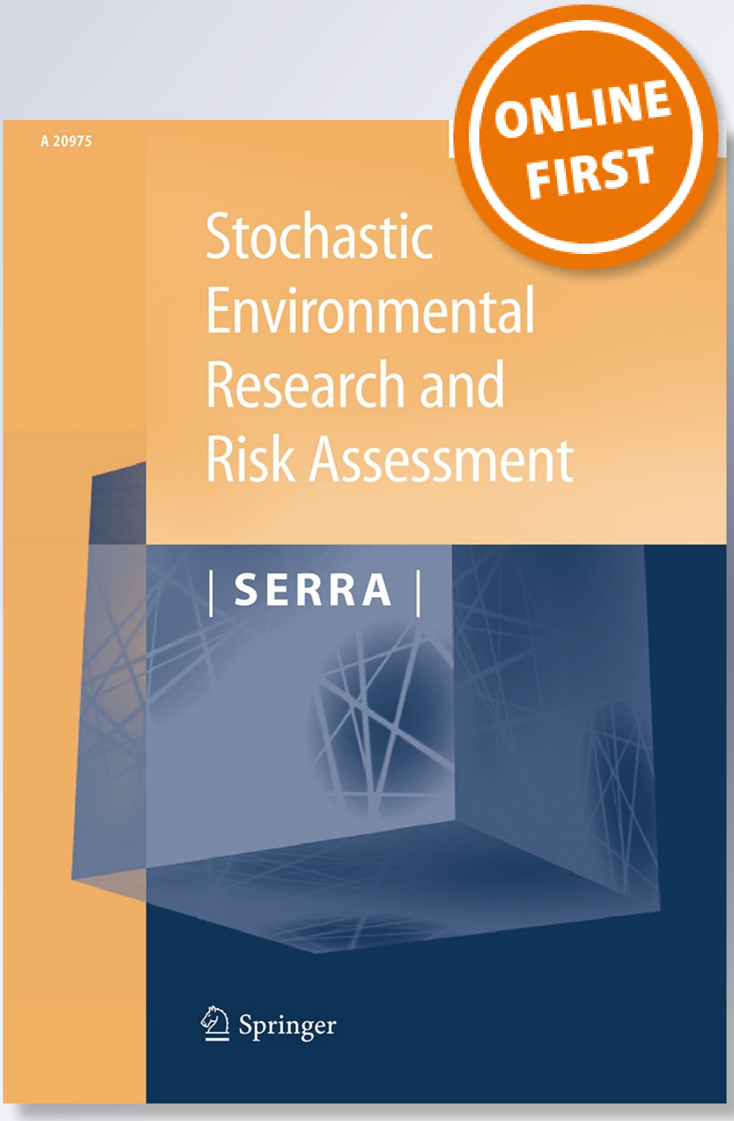

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ORIGINAL PAPER

Spatio-temporal trends of mean air temperature during 1961–2009 and impacts on crop (maize) yields in the most important agricultural region of Romania

Remus Prăvălie[1] · **Georgeta Bandoc**[1] · **Cristian Patriche**[2] · **Maria Tomescu**[3]

Abstract Climate change analysis is essential, considering the numerous economic and ecological implications of this critical global environmental issue. This paper analyzes the spatial and temporal trends of mean air temperature in Romania's most important agricultural area, the south and south-eastern region, between 1961 and 2009. In this respect, multiannual (the entire period) and multidecadal (1961–1990, 1971–2000, 1981–2009) trends were analyzed using the Mann–Kendall test and Sen's slope method at 23 weather stations, annually, seasonally and for the growing season of the region's main agricultural crops (maize and wheat). Multiannually, the results showed statistically significant temperature increases, on all temporal scales (maximum rate of 0.06 °C/year recorded in summer, equivalent to a net temperature rise of 2.82 °C), except for the autumn season (cooling without statistical significance). Multidecadally, the 1961–1990 period is marked by a general cooling, especially in autumn (maximum values of −0.07 °C/year or over 2 °C net cooling). In the 1971–2000 and 1981–2009 periods, a general warming was observed (maximum in summer for both multidecades, when positive rates peaked at 0.09 °C/year, or 2.5–3 °C net warming), but the warming of the last three decades is the most prominent in terms of spatial average magnitude and trend significance. Upon analysis of the impact of climate warming on agricultural yields (maize) through linear regression, in the 1991–2000 decade, considered as case study, it was found that in 32 % of the total analyzed area there are evident relationships between the two variables (*p* value <0.05). In this case, a dependency of 33–50 % (40 %, on average) of maize to climate was found, and a sensitivity (loss) ranging between 0.9 and 1.5 t/ha/year (1.2 t/ha/year, on average) for a 1 °C temperature rise. At the same time, significant losses (of up to 1.7 t/ha/year) of maize for a 1 °C temperature rise were identified in 51 % of the area, but with little p value significance (between 0.05 and 0.1). It is however necessary to analyse the agro-climatic results cautiously, considering that only one decade of climate-agriculture relationship was studied. The results can be useful first and foremost for mitigating the climate change impact on agricultural systems, by prioritizing future adaptation strategies enforced by policy makers.

Keywords Mean air temperature · Trends · Mann–Kendall · Sen's slope · Agricultural crops · Impact · Romania

1 Introduction

Climate change is one of the most critical global environmental issues, and is currently an exceeded planetary boundary, alongside two other global issues which are

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considered to be critical, i.e., biodiversity decline and the disturbance of the nitrogen biogeochemical circuit (Rockström et al. 2009). It is estimated that the current exceedance, in comparison with the pre-industrial era, of the 350 ppm threshold (currently ~400 ppm), under the action of anthropogenic CO_2 emissions, and of that of 1 W m^{-2} (currently ~1.5 W m^{-2}), considering radiative forcing, will increase the risk of triggering irreversible changes of the global climate system (Rockström et al. 2009; Steffen et al. 2011).

Global warming is currently the most worrisome form of manifestation of climate change. In the last approximately 100 years (1901–2012), the global mean air temperatures increased by 0.89 (0.69–1.08) °C, most of which occurred in the second half of the twentieth century, when it is estimated that the climate warmed by 0.72 (0.49 to 0.89) °C, in the period 1951–2012 (IPCC 2013). Spatially, temperature rise was obviously higher over land than ocean, and especially at high latitudes in the northern hemisphere. Thus, based on instrumental records, it is factually clear that, globally, the climate has gradually warmed since the end of the nineteenth century up to present day, which is confirmed by the first decade of the twenty first century, the warmest ever of all recorded observational data series (IPCC 2013).

Throughout this century, recent estimations indicate that climate warming is likely to exceed 2 °C over the period 2081–2100 (above 1850–1900 period) when considering scenarios RCP8.5, RCP6.0 (high confidence) and even RCP4.5 (medium confidence) (IPCC 2013). Given this context, there is a real threat to maintaining climate warming under the 2 °C limit in this century (above preindustrial levels), considered to be essential by international policies that aim to ensure the climate stability of the planet. At the same time, other estimations highlight the fact that, in case of atmospheric CO_2 concentrations doubling in comparison with the pre-industrial era (280 ppm), most climate models project mean global temperature rises of ~3 °C (±1.5 °C) (IPCC 2007; Rockström et al. 2009). However, this thermal threshold can be exceeded considerably when considering the slow positive feedback-type global warming autoacceleration mechanisms, which are triggered in certain tipping elements of the earth system, once a given tipping point is exceeded (Lenton et al. 2008). Changes in albedo values in the Arctic and Antarctic regions, along with the loss of ice surfaces, account for one of the most representative examples of these mechanisms (Nilsson et al. 2010; Lenton 2012; Wadhams 2012; Duarte et al. 2012). Therefore, if these additional factors are taken into consideration, there is a chance that, by the end of the century, mean global temperatures increase twice as much as the current climate model estimations (Hansen et al. 2008).

From an anthropic perspective, agriculture is one of the components which are most heavily affected by such climate system disturbances. Recent studies have shown that, over the past three decades (1980–2008), climate warming resulted in a general decline of mean global yields of the main crop types, i.e., 3.1 % for maize and 4.9 % for wheat (Lobell et al. 2011), which indicates that temperature is overall the most important climate parameter influencing major agricultural crop dynamics.

In Romania, in the past century (1901–2005), while the mean annual temperature increased by approximately 0.5 °C, in the second half (1961–2007) the net warming rate was roughly double, with values ranging from 0.8 to 1 °C (Busuioc et al. 2010). In the twenty first century, a climate warming of 1.4 °C (±0.4 °C) is foreseen in Romania (considering the A1B scenario) for the 2021–2050 period, and of 3.1 °C (±0.7 °C) for the 2071–2100 period, compared to the climate conditions recorded between 1961 and 1990 (Busuioc et al. 2010).

Therefore, in this context of strong temperature dynamics, the number of studies on mean or extreme temperature variability has increased significantly over the past decade. Representative studies for the entire Romanian territory (Tomozeiu et al. 2002; Busuioc et al. 2007; Sandu et al. 2008; Busuioc et al. 2010; Croitoru et al. 2012a; Ionita et al. 2013; Busuioc et al. 2014; Dumitrescu et al. 2014; Marin et al. 2014; Rimbu et al. 2014) identified evident changes in temperature dynamics, both annually and seasonally. In terms of mean temperatures, only positive annual trends were found over the past five decades, throughout the entire country, which is mostly due to the positive trends noticed in spring and especially in summer (Croitoru et al. 2012a; Dumitrescu et al. 2014; Marin et al. 2014). It was found that the total summer warming from 1961 to 2007 ranged between 1.6 and 2 °C in most of the country's territory, and that 5 out of the 6 hottest summers in the last century (1901–2007) were recorded in the 1999–2007 interval (Busuioc et al. 2007), thus highlighting the key-role this season's temperature dynamics had on annual thermal values over the past decades. The causes for this season's significant changes are governed by large-scale dynamic mechanisms (Ionita et al. 2013).

Countrywide studies performed on extreme temperatures generally pointed to climate warming in all seasons (which peaked in summer), except for autumn; the phenomenon is controlled, for the most part, by large-scale atmospheric circulation mechanisms (Tomozeiu et al. 2002; Busuioc et al. 2014; Rimbu et al. 2014). Regionally, significant differences were also found in terms of temperature dynamics. The results of various studies, based on mean/extreme temperatures, indicated an evident climate warming (in all seasons, except for autumn) in high altitude areas—in the Carpathian Mountains (Croitoru et al. 2012b;

Birsan et al. 2014; Cheval et al. 2014; Croitoru et al. 2014)—, as well as outside the mountainous region, such territories mainly consisting of lowlands (Piticar and Ristoiu 2012; Croitoru and Piticar 2013).

The present study aims to analyze mean air temperature changes over the past decades in the country's most important agricultural region, which corresponds to southern and south-eastern Romania. Unlike the previous studies performed on the parameter's regional dynamics, this study aims to generate new results by means of (1) a comprehensive analysis of annual and seasonal trends (in terms of rate values for each statistical significance threshold) in the multiannual period 1961–2009, (2) the first analysis of growing season trends of the two most important crops (maize and wheat), (3) the first investigation of multidecadal trends (1961–1990, 1971–2000 and 1981–2009) and (4) the first approach of the relationship between climate warming and agricultural (maize) yields by selecting the 1991–2000 decade as case study. Essentially, this paper aims to obtain significantly more detailed climatic results on the air temperature changes recorded over the past five decades, while at the same time addressing a major gap of Romanian climate studies—the impact of climate warming on agricultural system dynamics.

2 Data and methods

2.1 Study area

The study area is located in Romania's extra-Carpathians region, and covers the southern and south-eastern territory (Fig. 1). It features three major landforms (Romanian Plain, Dobrogea Plateau, Danube Delta), which correspond to the following geographic coordinate intervals: 43°37′–46°5′N, and 22°27′–29°43′E. The analyzed area totals ~63,600 km^2, which makes approximately 26.7 % of the country's area (238,391 km^2).

Although the study area covers an altitude range of less than 500 m (the maximum altitude is found in northern Dobrogea, and the minimum in the Danube Delta) (Fig. 1),

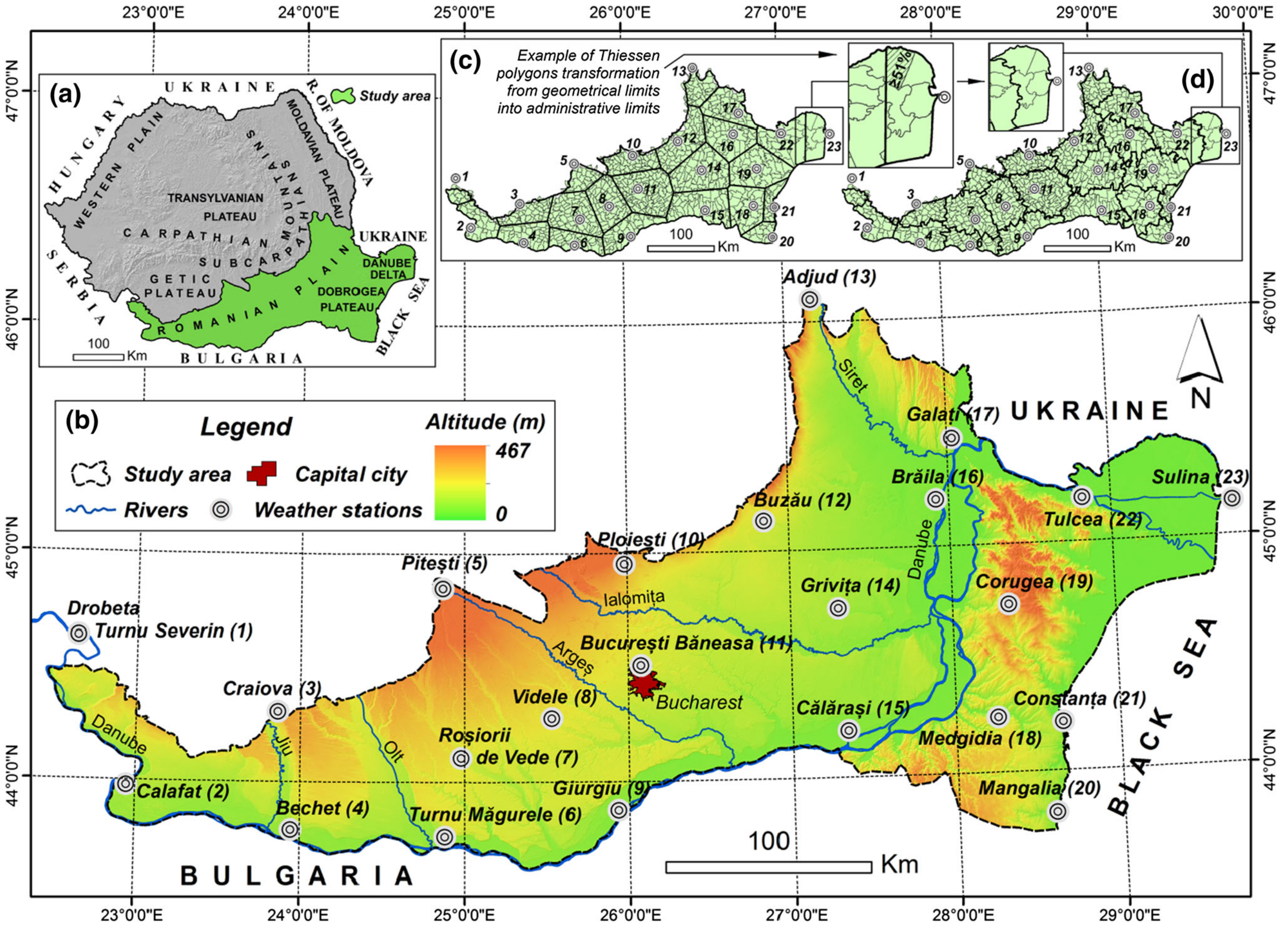

Fig. 1 Study area in Romania (**a**) and the locations of the analyzed weather stations (**b**); geometric (**c**) and administrative (**d**) delineation of Thiessen polygons

the climate regime is complex, as it is mainly dominated by Mediterranean influences in the west, continental in the central and central-eastern part and Black Sea influences in the east (Bogdan 2005a, b; Sandu et al. 2008).

Thermally, the Mediterranean influences account for higher temperatures in the warm season and moderate ones in the cold season, due to warm tropical air advections (coming from the Mediterranean Sea) typical for Romania's south-western region. Continental influences generally cause lower temperatures in the cold season and higher ones in the warm season, due to the transport (from the Eurasian region) of cold continental air, during winter, and of warm tropical or continental air, during summer. The Black Sea plays a moderating role especially in the shore region, where temperatures are higher in winter and lower in summer, when compared to Dobrogea inland territories.

The thermal potential of the study area is the highest countrywide (especially in the south-western, southern and south-eastern extremities). While mean annual temperatures range between 9.7 °C (Adjud station, north-east of the study area) and 12.2 °C (Drobeta Turnu Severin, south-west), there are however significant seasonal differences, both in terms of calendar seasons and growing seasons of the main agricultural crops, i.e., April–October (maize growing season) and October–June (wheat growing season) (Table 1). Therefore, in the cold season (winter) mean temperatures range between −1.5 and 2.2 °C, while in the warm season (summer) between 20 and 22.6 °C (Table 1). In transitional seasons, mean thermal values fall between 9.5 and 12.4 °C (spring) and 10 and 13.2 °C (autumn), while the growing seasons of maize and wheat prompt values of 16…18.5 °C and 6.6…9.1 °C, respectively (Table 1).

Therefore, considering the high annual temperature values, which determine high annual potential evapotranspiration values (generally exceeding 800 mm) (Croitoru et al. 2013a), along with the lowest annual precipitation amounts ($\sim$500–600 mm in the west and approximately 300–400 mm in the east), it results that the study area has the highest annual climatic water deficit (approximately

Table 1 Geographic coordinates and mean multiannual temperatures (1961–2009) at the analyzed weather stations (*A* annual, *W* winter, *Sp* spring, *Su* summer, *Au* autumn, *Apr–Oct* maize growing season, *Oct–Jun* wheat growing season)

No.[a]	Weather stations	Latitude	Longitude	Alt. (m)	Mean temperature values (°C)						
					A	W	Sp	Su	Au	Apr–Oct	Oct–Jun
1	Drobeta T. Severin	44°37′35″	22°37′34″	78.2	12.2	1.2	12.3	22.5	12.8	18.5	9.1
2	Calafat	43°59′06″	22°56′46″	62.2	11.7	0.5	12.0	22.4	11.9	18.2	8.5
3	Craiova	44°18′37″	23°52′01″	193.2	11.3	−0.1	11.6	21.8	11.9	17.7	8.1
4	Bechet	43°47′23″	23°56′39″	37.2	11.3	−0.2	11.9	22.2	11.4	17.9	8.1
5	Pitesti	44°50′56″	24°51′58″	317.2	10.1	−0.2	10.1	20.0	10.4	16.0	7.1
6	Turnu Magurele	43°45′37″	24°52′42″	31.6	12.0	0.3	12.4	22.6	12.5	18.5	8.7
7	Rosiorii de Vede	44°06′26″	24°58′43″	103.4	10.9	−0.9	11.2	22.0	11.3	17.6	7.6
8	Videle	44°16′58″	25°32′13″	107	10.9	−0.8	11.2	21.9	11.2	17.5	7.6
9	Giurgiu	43°52′31″	25°55′58″	24.8	11.4	−0.3	11.9	22.5	11.7	18.1	8.2
10	Ploiesti	44°57′21″	25°59′15″	178.2	10.3	−0.8	10.5	21.0	10.7	16.7	7.2
11	Bucuresti Baneasa	44°30′38″	26°04′41″	91.2	10.6	−0.7	10.9	21.4	10.7	17.1	7.4
12	Buzau	45°07′58″	26°51′06″	98.3	11.0	−0.2	11.1	21.8	11.4	17.5	7.8
13	Adjud	46°06′17″	27°10′13″	101.9	9.7	−1.5	10.0	20.4	10.0	16.2	6.6
14	Grivita	44°44′27″	27°17′41″	51.1	10.7	−0.7	10.9	21.6	11.0	17.3	7.5
15	Calarasi	44°12′21″	27°20′18″	19.9	11.9	0.7	11.9	22.3	12.6	18.2	8.7
16	Braila	45°12′24″	27°55′11″	15.7	10.8	−0.5	10.9	21.7	11.2	17.3	7.6
17	Galati	45°28′23″	28°01′56″	70.3	10.8	−0.6	10.8	21.7	11.3	17.4	7.5
18	Medgidia	44°14′36″	28°15′05″	70.7	11.2	0.7	10.6	21.4	11.9	17.2	8.1
19	Corugea	44°44′04″	28°20′31″	220.4	10.1	−0.8	9.5	20.7	10.8	16.3	6.9
20	Mangalia	43°48′58″	28°35′15″	7.2	11.6	2.2	9.9	21.3	13.2	17.1	8.6
21	Constanta	44°12′50″	28°38′44″	14	11.8	1.9	10.3	21.8	13.2	17.6	8.7
22	Tulcea	45°11′26″	28°49′27″	5.6	11.2	0.5	10.8	21.8	11.6	17.4	8.1
23	Sulina	45°08′54″	29°45′32″	13.4	11.6	1.5	10.0	21.8	13.1	17.5	8.4

[a] Stations are ordered from west to east, based on increasing longitude coordinate values

−200 mm in the west and −400 mm in the east), and is considered to be Romania's most arid region (Păltineanu et al. 2007).

Socio-economically, the study area is of utmost national importance. It is the country's main agricultural region, seeing as it covers almost 40 % (47,879 km^2) of the total agricultural land in Romania (~122,000 km^2) (CLC 2006). Most of the land is arable (maize and wheat are the main crops) and totals 44,562 km^2 (70 % of the study area), corresponding to 47 % of the country's total arable land (~95,000 km^2) (CLC 2006).

At the same time, it is a densely populated (~7.9 mil inhabitants on January 1st, 2015, 35 % of the country's total population, according to the data provided by the "Romanian National Institute of Statistics") and highly economically developed region (2663 establishments, of which 60 are cities, including the capital, the country's main industrial and economic center), with numerous industry, transportation and tourism-related activities.

Therefore, considering the climate (especially the major importance of temperature) and socio-economic aspects (especially agriculture, which is generally the anthropogenic component with the highest dependency on climate conditions), the south and south-eastern region of Romania was considered to be representative for the analysis of mean air temperature trends over the past half-century, both annually and seasonally (the four calendar seasons), as well as for the vegetation periods of the region's main agricultural crops.

2.2 Climate data

In order to investigate the general (mean) temperature dynamics against the background of global climate change, the climate trend analysis in the present study was performed based on mean monthly air temperature data (°C), collected from 23 weather stations distributed uniformly throughout the study area (Fig. 1; Table 1). The data series cover the 1961–2009 period, and were provided by the National Meteorology Administration (mean monthly data for the weather stations in Table 1; Fig. 1 numbered 2, 4, 5, 8, 9, 10, 13, 14, 16, 18, 19 and 20) and the ECA&D data platform (daily data based on which the mean value was obtained for the remaining weather stations) (Klein Tank et al. 2002), both data sources homogeneously covering the 49 years. The 49-year analysed period was influenced by ECA&D climate data, available for the studied cases (and, generally, for the Romanian territory) up to 2009.

Almost all analyzed weather stations provided continuous data series for the entire study period, with a few exceptions (stations 1, 6, 15, 18, 20 and 22) where, due to the impossibility of acquiring monthly data for several years, the data was estimated on the basis of the continuous data series from closest weather stations, using linear regression technique (the estimated data is considered to be accurate, as *r* correlation coefficient values are very high, i.e., close to 1 in most cases).

Finally, the monthly climate data of the 23 weather stations were used for computing mean air temperature values annually (for the 12 months), seasonally (winter: December–February; spring: March–May; summer: June–August; autumn: September–November) and for the growing seasons of the main agricultural crops, i.e., maize (April–October) and wheat (October–June).

2.3 Agricultural data

Finally, the present study also tests the hypothesis of the relationship between temperature dynamics and agricultural yields in the region. To this end, maize (*Zea mays* L.) yields were used, expressed in tonnes/hectare/year in the case study decade 1991–2000. The data were provided by the "Romanian National Institute of Statistics"—RNIS, for 783 territorial administrative-units (TAU) overlapping the study area (the administrative units with borders exceeding the natural northern limit of the study area were included in the analysis if at least 51 % of their surface overlapped the study area, as it is assumed the highest productions were recorded in these sections).

The reason for choosing a relatively limited analysis period, i.e., a decade, is related to the availability of national agricultural production data. In Romania, real and accurate agricultural data are available at TAU level only for the 1990–2003 period. Although earlier TAU information exists, it cannot be used due to communist era-specific distortions, as implausible data were consistently being reported in order to maintain a seemingly high agricultural productivity. After 2003, the data were recorded at company/county level, and a concrete spatial analysis is therefore not possible. As a consequence, the period of choice was based on the available data, and the 10-year period was selected in order to cover a decade of the multidecadal period analysed in terms of climate, 1981–2009.

At the same time, maize was chosen as case study for the analysis of the impact of climate warming on agricultural production considering the cultivated area (which exceeds that of wheat, according to RNIS database investigations) and its growing season, which overlaps the period with the highest climatic stress (summer months). Other reasons for which only maize was chosen for the analysis of the relationship between climate and agriculture relate to the nature of data (maize production is recorded by RNIS separately, as opposed to wheat, for which data is recorded in combination with rye), and to its vulnerability to climate change, which recent research studies confirm to be the greatest of all major agricultural crops (Lobell et al. 2011).

2.4 Methods

2.4.1 Trend detection and annual temperature rate computation

Trend detection and temperature magnitude computation were performed for each weather station, on the seven temporal scales (annual, four calendar seasons and two growing seasons). Trend analyses were carried out multiannually (for the entire period 1961–2009) and multidecadally (for the periods 1961–1990, 1971–2000 and 1981–2009), and the results were represented by means of GIS techniques (ArcGIS 10.1). The multidecadal analysis was deemed necessary in order to identify the most recent climate cooling/warming variations, in accordance with the minimum 30-year period recommended by the World Meteorological Organization for climate-related analyses (the period 1981–2009 is considered to be representative, given the closeness of the 29 years).

The MAKESENS Excel application, developed by the Finnish Meteorological Institute (Salmi et al. 2002), was used for trend detection and estimation. The application operates with two types of statistical analyses, including the non-parametric Mann–Kendall test, for increase/decrease monotonic trend detection, and the non-parametric Sen's slope method, for linear trend magnitude quantification (Gilbert 1987; Salmi et al. 2002). Trend detection through the Mann–Kendall method was based on Z (considering that this procedure operates on a value number of $n \geq 10$), and the quantification of trend slopes (as change per year) was based on the Q estimator of the Sen's method (Gilbert 1987; Salmi et al. 2002).

Both methods were used in their basic forms. The testing of the trends' statistical significance was done in relation to the application's α thresholds (two-tailed test), i.e., 0.1, 0.05, 0.01 and 0.001 (corresponding to confidence levels of 90, 95, 99 and 99.9 %), which have been integrally used in numerous studies on temperature variability (Mohsin and Gough 2010; Croitoru et al. 2012a; Ageena et al. 2014; Appiotti et al. 2014; Cheval et al. 2014). In addition to positive/negative trends, the study also considered stationary trends, defined by a slope value of 0.000 (Croitoru et al. 2013b).

Statistically, the two methods are highly advantageous for climate data analysis, as they do not require a specific type of statistical distribution, and they provide the possibility to operate even in the cases of missing values or the presence of outliers. Given this context, the two methods are widely used in specialized literature focusing on climatic data trend analysis (Tabari and Hosseinzadeh Talaee 2011; Wang and Zhang 2012; Croitoru et al. 2013a, b; Meng et al. 2013; Tabari and Hosseinzadeh Talaee 2013; Wang et al. 2013; Ageena et al. 2014; Appiotti et al. 2014; Dumitrescu et al. 2014; Liu et al. 2014; Tao et al. 2014; Khalili et al. 2015; Prăvălie and Bandoc 2015; Bandoc and Prăvălie 2015; Tabari et al. 2015; Zhang et al. 2015; Zhu et al. 2015 etc.).

2.4.2 Spatializing net temperature change through interpolation methods

In addition to the annual rates detected with the Sen's slope method, this paper entailed the analysis and spatialization of net temperature changes on the seven temporal scales, multiannually (total changes over the 49-year period) and multidecadally (total changes over 30/29-year intervals).

Spatial interpolation of net temperature changes was done generally through the ordinary kriging method, by means of the Geostatistical Analyst module of the ArcGIS 10.1 software, except for several cases in which the universal kriging and co-kriging methods, which uses altitude as an auxiliary variable, generated better results (1961–2009 autumn, 1961–1990 spring, 1971–2000 summer and 1981–2009 spring and maize growing season).

2.4.3 The analysis of the relationship between temperature and maize yields

This approach sought to statistically quantify the possible impact of air temperature dynamics on maize yield in the period 1991–2000. This analysis was conducted in three main phases. In the first phase, the areas of influence of the meteorological stations in adjacent areas were identified by means of Thiessen–Voronoi polygons (Fig. 1c). Subsequently, the geometric polygon boundaries were modified in accordance with the administrative units overlapping the Thiessen polygons by at least 51 %, assuming that higher agricultural yields had occurred in these sections (Fig. 1d). Therefore, considering the fact that the initial Thiessen geometric boundaries did not accurately incorporate the administrative units they encompassed, this modification was deemed necessary in order for the two types of data to be extracted/analysed in spatially continuous conditions, in identical territorial units. In the end, the resulting Thiessen climatic units (TCU) can be considered compact climate zones (Fig. 1d), in which agro-climatic data can be clustered for statistical analysis (Prăvălie et al. 2014b, 2016).

The second phase was based on agro-climatic data extraction from the 23 TCUs. The climatic data were extracted by averaging pixel values for each of the 23 TCUs, for every year from 1991 to 2000. Obtaining pixel values was made possible by interpolating average temperatures (by means of the hybrid regression—kriging method) during growing season of maize based on the data provided by the 23 weather stations. Finally, the second data category (agricultural), was obtained by averaging the maize yields recorded in all TAU included in the final Thiessen units (in the limited cases of administrative units for which there was no information, the available TAU data were averaged).

The third phase focused on the analysis of the statistical relationship between climate and agricultural data, based on the regression method. In this phase, the mean extracted data were checked in terms of normal distribution using the Shapiro–Wilk test (Royston 1982), which showed that all data samples met the normality criterion. Subsequently, the regression analysis was performed using the XLSTAT trial version software. Finally, the models' statistical significance was considered high, for p values less than 0.05, and low, for p values between 0.05 and 0.1.

3 Results

3.1 General overview of temperature changes

By using the vector grid method by means of GIS techniques (Prăvălie et al. 2014a), in order to obtain a general trend assessment, results on annual changes in mean air temperature highlighted strong dynamics in the trends' multiannual and multidecadal profiles (Fig. 2).

It was thus noticed that, during the multiannual period 1961–2009, general annual and seasonal warming trends were recorded, except for the autumn season, when a general air temperature decrease trend was found for most of the weather stations. Considering the differences between the most significant warming rate values, recorded in summer (maximum of 0.06 °C/year), and cooling rates, recorded in autumn (maximum −0.02 °C/year), a significant amplitude of multiannual variability rates of 0.08 °C/year (Fig. 2) becomes apparent.

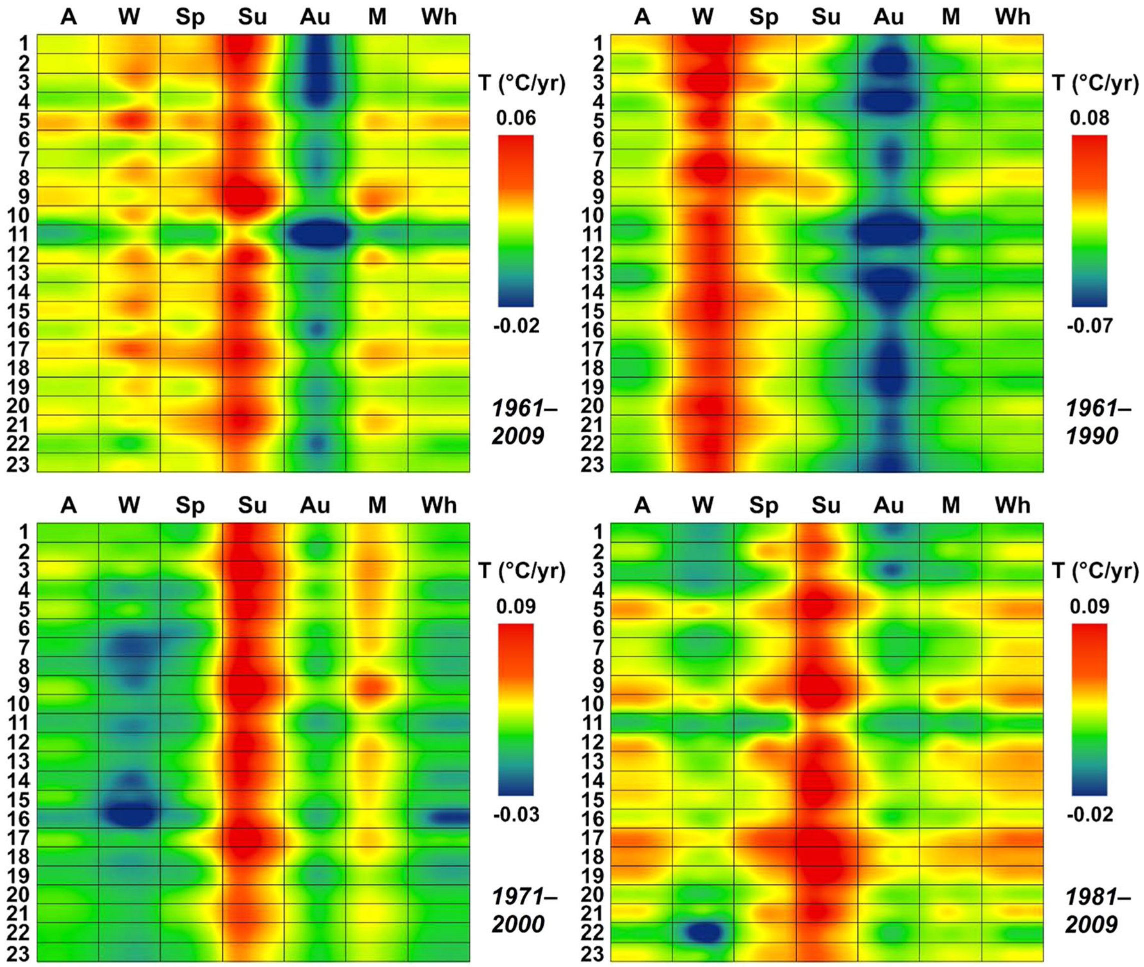

Fig. 2 General overview of temperature (T) changes on the seven temporal scales (*A* annual, *W* winter, *Sp* spring, *Su* summer, *Au* autumn, *M* maize growing season, *Wh* wheat growing season), multiannually and multidecadally (1…23—weather stations ordered according to Fig. 1; Table 1)

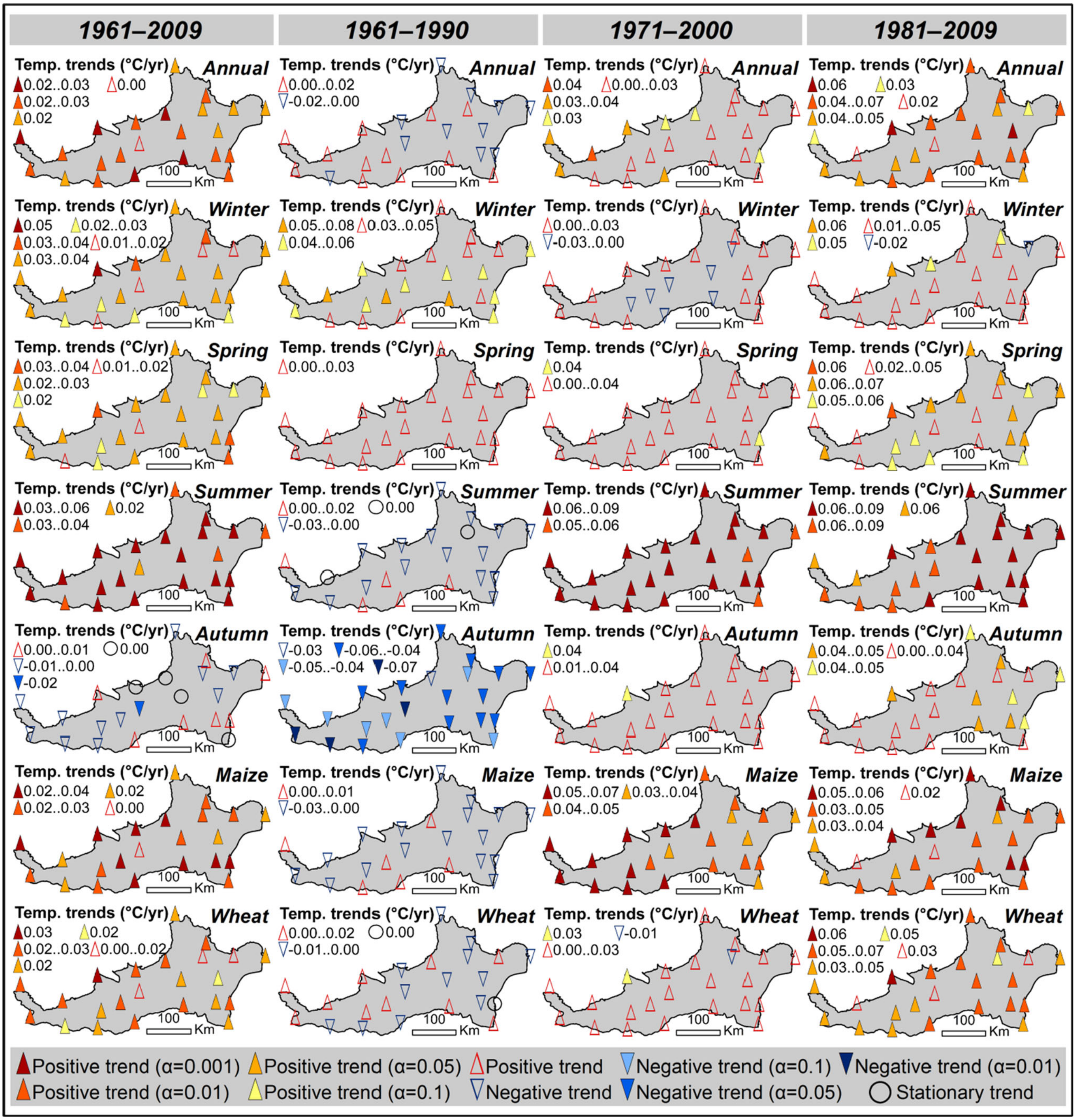

Fig. 3 Air temperature trends (direction, magnitude and statistical significance) on the seven temporal scales, multiannually (1961–2009) and multidecadally (1961–1990, 1971–2000, 1981–2009). *Note* stationary trends were identified considering a slope value of 0.000 (instances with the third decimal place equal to at least 1 indicate positive/negative trends)

Multidecadally, two general instances were identified. The first covers the period 1961–1990, characterized by general climate cooling with certain warming exceptions, i.e., the winter and spring seasons (Fig. 2). Considering the maximum differences between the thermal rates identified for winter and autumn, a high climate variability amplitude can be noticed, i.e., 0.15 °C/year. The second instance refers to the last two periods, for which a general climate warming trend was found. Considering the highest rate differences (identified in summer–winter for both periods), an important climate variability can be noticed, which consists in amplitudes of 0.12 °C/year (1971–2000) and 0.11 °C/year (1981–2009), respectively (Fig. 2).

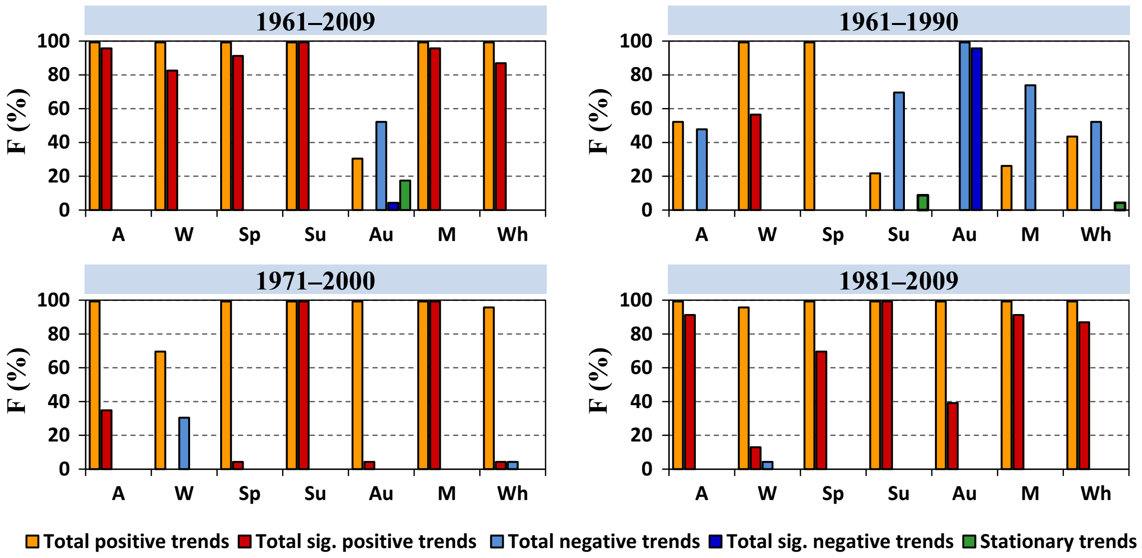

Fig. 4 Trends frequency (multiannual and multidecadal) of air temperature on the seven temporal scales (*A* annual, *W* winter, *Sp* spring, *Su* summer, *Au* autumn, *M* maize growing season, *Wh* wheat growing season), according to direction (positive/negative/stationary) and statistical significance (significant/insignificant)

Table 2 Mean spatial values of multiannual and multidecadal trend magnitudes (°C/year), on the seven temporal scales (*A* annual, *W* winter, *Sp* spring, *Su* summer, *Au* autumn, *Apr–Oct* maize growing season, *Oct–Jun* wheat growing season

Time	1961–2009	1961–1990	1971–2000	1981–2009
A	0.02	0.00[a]	0.02	0.05
W	0.03	0.05	0.01	0.03
Sp	0.03	0.02	0.02	0.05
Su	0.04	−0.01	0.08	0.08
Au	0.00[a]	−0.05	0.02	0.03
Apr–Oct	0.02	−0.01	0.05	0.04
Oct–Jun	0.02	0.00[a]	0.02	0.05

[a] The values are negative, considering the third decimal place

3.2 Spatial analysis of temperature annual changes

The Mann–Kendall and Sen's slope methods were used for detecting and quantifying trend magnitudes, and the results showed a considerable climate variability. The 1961–2009 period is characterized by general climate warming. Annually, temperature increase trends were detected for all weather stations (with a maximum rate of 0.031 °C/year in the northern extremity, at Pitesti station). Almost all these trends are statistically significant, with high and very high α thresholds (Figs. 3, 4).

In terms of climate seasons, positive trends were detected for all weather stations in winter, spring and summer, with maximum warming rates in summer (the maximum of 0.058 °C/year was recorded in the south, at Giurgiu station). Thus, the summer season has the highest contribution to climate warming, characterized by 100 % statistically significant trends (all 23 weather stations), of which almost 80 % were at the maximum confidence threshold $\alpha = 0.001$ (Figs. 3, 4). As expected, the highest value of mean spatial warming (the average rate values of all weather stations), i.e., 0.04 °C/year, was recorded in this season (Table 2).

While autumn is the only season with predominantly negative trends (52 % of the weather stations), a single case is statistically significant (Figs. 3, 4). Generally, these trends show low rates of climate cooling (the average cooling trend, −0.003 °C/year, being close to stationarity) (Table 2). There are also instances of punctual warming and stationarity (48 % of the weather stations). The two vegetation seasons show warming trends exclusively, with higher values in terms of statistical confidence and magnitude for the maize growing season (Figs. 3, 4).

Multidecadally, the 1961–1990 period contains three instances of temperature dynamics, i.e., exclusively negative trends (autumn), mixed trends (in most of the analyzed temporal trends—annual, summer, crop growing seasons) and exclusively positive trends (winter and spring) (Fig. 3). However, they have no statistical confidence, except for winter (13 cases with warming trends, equivalent to 57 % of the total) and autumn (considerable cooling, significant in 96 % of cases; the maximum value of the temperature decrease rate, −0.071 °C/year, was recorded at the Bucharest station) (Figs. 3, 4). Moreover, these two seasons also stand out in terms of their extreme mean spatial trends (0.05 °C/year average warming in winter, and −0.049 °C/year average cooling in autumn) (Table 2).

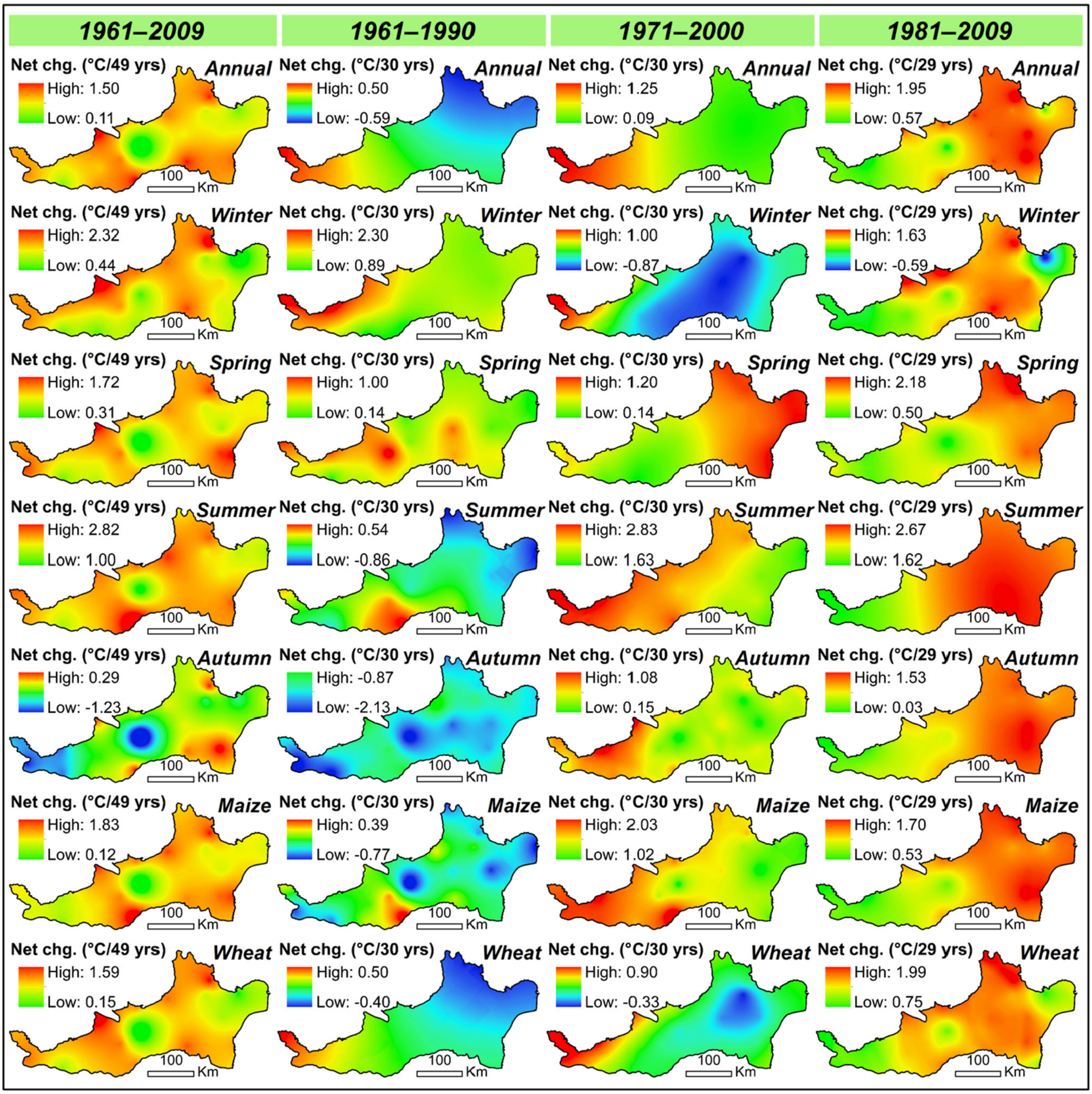

Fig. 5 Net air temperature changes on the seven temporal scales, multiannually (1961–2009) and multidecadally (1961–1990, 1971–2000, 1981–2009)

The 1971–2000 period marks the beginning of climate warming. Thus, except for winter (mixed trends), all analyzed temporal scales are characterized by exclusively/almost exclusively increasing temperature trends (Fig. 3). In terms of statistical significance and magnitude these trends are most evident in summer and during maize growing season (exclusive statistical significance in both cases, with a maximum increase rate in the summer season of 0.094 °C/year, at the Giurgiu station) (Figs. 3, 4). On average, warming rates reached 0.075 °C/year in the summer, and 0.048 °C/year in the growing season of maize (Table 2). Trends with an evident statistical significance percentage (35 %) were also observed annually, when trend magnitude reached the maximum rate of 0.042 °C/year (in west, at Craiova station) (Fig. 3).

Table 3 Mean spatial values of multiannual and multidecadal net trend magnitude (°C/49/30/29 years), on the seven temporal scales (*A* annual, *W* winter, *Sp* spring, *Su* summer, *Au* autumn, *Apr–Oct* maize growing season, *Oct–Jun* wheat growing season)

Time	1961–2009	1961–1990	1971–2000	1981–2009
A	1.06	−0.05	0.71	1.37
W	1.38	1.49	0.20	0.87
Sp	1.30	0.48	0.68	1.51
Su	1.96	−0.18	2.26	2.22
Au	−0.15	−1.48	0.64	0.94
Apr–Oct	1.20	−0.20	1.43	1.24
Oct–Jun	1.04	−0.02	0.47	1.46

The most significant climate warming, in terms of magnitude/spatial average magnitude and trend significance, was identified in the 1981–2009 period. The past three decades show the most obvious warming, considering the total/near-total statistical significance of the 5 temporal scales (annual, spring, summer and crop growing seasons), and the partial significance in winter and autumn (Figs. 3, 4). In this period, summer shows the highest warming, in terms of spatial average value (0.076 °C/year), point value (0.092 °C/year in the east, at Corugea station) and statistical significance (100 % significance, of which ~60 % at $\alpha = 0.001$) (Figs. 3, 4, Table 2). Except for one isolated case of insignificant cooling in winter, at a northeast weather station, a generalized climate warming can therefore be observed in the last three decades for all analyzed cases (Fig. 3).

3.3 Spatial analysis of temperature net changes

In this paper it was considered that air temperature net changes (total modifications over the 49 years for the multiannual status, and on 30/29 years for the multidecadal one) are highly appropriate for highlighting the general climate warming, which is why they were spatialized by means of interpolation methods, for each temporal scale of the 1961–2009 period, and for the three periods separately analyzed (Fig. 5).

Therefore, the multiannual period-oriented analysis indicated a net climate warming which peaked at 1.5 °C on the annual scale, and at 2.8 °C on the climate season scale (summer) (Fig. 5). The growing seasons also had significant warming that exceeded 1.5 °C. Autumn had an overall climate cooling, maximal (over 1 °C) in the central part of the study area (Fig. 5). On average, the maximum net warming reached almost 2 °C in the summer season (Table 3).

The 1961–1990 period featured significant temperature decreases, which were maximal in autumn, when the punctual cooling exceeded 2 °C, and the average cooling reached approximately 1.5 °C (Fig. 5; Table 3). Particular warming instances showed 1 °C in spring, but exceeded 2 °C in winter (this season also shows significant spatial average warming of ~1.5 °C) (Fig. 5; Table 3).

The 1971–2000 period evinced accelerated warming especially in summer (punctual warming of up to 2.8 °C, and spatial average warming of 2.3 °C) and during the maize growing season (maximum punctual of 2 °C, and maximum average of almost 1.5 °C) (Fig. 5; Table 3). While a limited climate cooling instance was identified in the wheat growing season, the process is more representative for winter, in terms of both area coverage and magnitude (Fig. 5).

The past three decades, 1981–2009, are marked by the highest total climate warming given the fact that four temporal scales show maximal punctual values of almost 2 °C or beyond (annual, spring, summer, wheat growing season), and three exceed 1.5 °C (winter, autumn, maize growing season) (Fig. 5). In terms of average spatial warming, this period is significant mainly due to the highest temperature increase net rates of all analyzed periods (1961–2009/multidecadal periods), except for winter, summer and maize growing season (Table 3).

3.4 Assessing the impact of temperature change on maize production

The analysis of the influence of mean temperature dynamics on maize yield in the study case period 1991–2000 produced diverse results, which must however be interpreted cautiously, considering the relatively limited period of the case study. By means of the linear regression method, it was found that determination coefficients (R^2) show high statistical significance (p value <0.05) in 35 % of the 23 TCU cases, and low significance in 43 % of the total (p values between 0.05 and 0.1; this significance class was taken into account due to the fact that it was considered that certain instances with p values close to the 0.05 threshold, such as 0.056, cannot be omitted) (Table 4). Moreover, in 22 % of cases, regression models show no statistical confidence.

It was noticed that, in high significance cases (which total ~20,400 km^2, 32 % of the analyzed area), temperature dynamics accounted for 33 % (Constanta TCU, in the south-east of the study area) to 50 % (Adjud TCU, in the north-east) of maize production variation (Table 4). On average, this climate-production dependence almost reaches 40 %. Upon analysis of slope values, which indicate an inverse relationship between the two variables (increasing temperature—decreasing yields), it was noticed that a 1 °C temperature increase determined maize production losses ranging from 0.9 t/ha/year (Corugea TCU, in the east) to 1.5 t/ha/year (Calafat TCU, in the west) (Table 4). On average, the losses corresponding to a 1 °C temperature rise are of 1.2 t/ha/year.

While various cases of dependence/sensitivity of maize crops to temperature were detected in the low significance

Table 4 Regression analysis parameters for the twenty three Thiessen climate units

No.[a]	Thiessen climatic units	Sample size	Intercept	Slope	R^2 adjusted	R	p value	Significance[b]
1	Drobeta T. Severin	10	33.909	−1.656	0.287	−0.605	0.064	Low
2	Calafat	10	31.065	−1.484	0.342	−0.644	0.044	High
3	Craiova	10	27.999	−1.390	0.432	−0.704	0.023	High
4	Bechet	10	24.289	−1.159	0.299	−0.613	0.059	Low
5	Pitesti	10	11.318	−0.500	0.066	−0.412	0.237	Not significant
6	Turnu Magurele	10	28.338	−1.381	0.374	−0.666	0.035	High
7	Rosiorii de Vede	10	24.129	−1.204	0.307	−0.619	0.056	Low
8	Videle	10	16.726	−0.801	0.228	−0.560	0.092	Low
9	Giurgiu	10	20.036	−0.944	0.177	−0.518	0.125	Not significant
10	Ploiesti	10	17.073	−0.780	0.173	−0.514	0.128	Not significant
11	Bucuresti Baneasa	10	19.487	−0.916	0.257	−0.583	0.077	Low
12	Buzau	10	18.891	−0.892	0.289	−0.607	0.063	Low
13	Adjud	10	25.320	−1.278	0.495	−0.724	0.014	High
14	Grivita	10	21.740	−1.008	0.380	−0.700	0.034	High
15	Calarasi	10	19.032	−0.852	0.240	−0.569	0.086	Low
16	Braila	10	21.901	−1.052	0.258	−0.584	0.077	Low
17	Galati	10	19.770	−0.961	0.350	−0.650	0.042	High
18	Medgidia	10	17.221	−0.817	0.259	−0.584	0.076	Low
19	Corugea	10	18.737	−0.946	0.389	−0.676	0.032	High
20	Mangalia	10	11.722	−0.497	0.110	−0.457	0.184	Not significant
21	Constanta	10	20.618	−0.977	0.330	−0.636	0.048	High
22	Tulcea	10	17.577	−0.858	0.259	−0.584	0.076	Low
23	Sulina	10	24.812	−1.257	0.032	−0.373	0.288	Not significant

[a] Thiessen units are ordered from west to east, based on increasing longitude coordinate values of the weather stations

[b] Statistical significance is considered high, for p values <0.05, and low, for p values between 0.05 and 0.1

Thiessen units (totaling $\sim$32,500 km^2, 51 % of the total), they should be regarded with caution given the expansion of the significance threshold to 0.1. In this instance, the maximum dependence of maize yields to climate warming did not exceed 31 % (Rosiorii de Vede Thiessen unit) (Table 4), and the average was 27 %. In terms of sensitivity, maize production losses (for a 1 °C temperature increase) ranging from 0.8 t/ha/year in the Videle climate zone to 1.7 t/ha/year in Drobeta TCU (with an average loss of 1 t/ha/year) were observed (Table 4). Finally, considering all cases with p value <0.1, the mean values of the temperature—maize relationship reached 32 % in terms of dependence (R^2 values), and 1.1 t/ha/year, in terms of sensitivity (slope values).

4 Discussions

4.1 Air temperature changes in the 1961–2009 period and the main control variables

Climatically, the results on multiannual temperature trends are consistent with the general global climate warming noticed over the past 50 years (IPCC 2007). At the same time, the multidecadal results support the accelerated global climate warming noticed after 1980 (IPCC 2007), similarly to the strongest warming trends identified in the last three decades in the study area. Similar instances can also be found for the European continent (Klein Tank et al. 2002, 2005).

At the same time, the multiannual results are consistent with previous studies on mean annual and seasonal temperature dynamics (most of which start with 1961), carried out at regional and national scales (Busuioc et al. 2010; Croitoru et al. 2012a, b, 2014; Piticar and Ristoiu 2012; Ionita et al. 2013; Dumitrescu et al. 2014; Marin et al. 2014). These studies indicated an overall annual and seasonal warming in the past half-century, except for the autumn season, for which a cooling trend was found, with no statistical significance, however. Nevertheless, a direct comparison with these previous studies can only be performed multiannually (as, according to our knowledge, there are no studies on successive multidecadal periods), but only for the annual and seasonal scales (as there are no analyses in the growing seasons of the major crops in the study area and in the country) and only in terms of the trends' signs and general significance (as detailed approaches, on trend magnitude and statistical significance for each α threshold, at each weather station, are generally missing). Also, a comparison in terms of net rates (multiannual/multidecadal) cannot be performed due to the same reasons.

The causes of seasonal climate warming (in the multiannual period) are connected to large-scale atmospheric circulation mechanisms. Detailed studies showed that the warming of winter, spring and summer coincides with temperature rises at 850 hPa and with the increase in high altitude anticyclons intensity and frequency (positive anomalies at 500 hPa), which determines more significant air temperature increase especially in summer (Busuioc et al. 2010).

At the same time, it was found that the climate warming of the past decades was influenced to a high extent by the North Atlantic Oscillation (NAO) mechanism, more specifically by its positive phase, which accounts for higher temperatures especially in winter (Bojariu and Giorgi 2005). Another mechanism which directly influences climate warming escalation is Atlantic Multidecadal Oscillation (AMO), the positive phase of which, coupled with the positive anomalies of water surface temperatures in the North Atlantic, determined increasingly warm summers especially after 1990 (Ionita et al. 2013).

In addition to these large-scale influence mechanisms, in non-mountainous regions of Romania there are other local factors which influence climate warming. A relevant example is the Black Sea water mean temperature increase after 1980 (at a rate of 0.06 °C/year in the 1982–2002 period) (Ginzburg et al. 2008), which may account to a certain extent for temperature dynamics, at least in the eastern sector of the study area.

Regarding the climate cooling found for the autumn season (multiannual regime), it is due, for the most part, to anticyclonic structure diminishment (in favor of cyclonic ones), as well as to air temperature decrease at 500 hPa and 850 hPa levels (Busuioc et al. 2010).

4.2 Negative consequences of climate warming on regional agricultural systems

Presently, climate changes are already causing significant modifications in agricultural systems in various regions of the Globe (Lobell et al. 2011; Olesen et al. 2011; Zhang et al. 2014; Verón et al. 2015). For instance, in was found that, in the 1980–2008 period, climate changes generated globally, through temperature (mainly) and precipitation dynamics, significant diminutions of the major agricultural productions of wheat (−5.5 %), maize (−3.8 %), soy (−1.7 %) and rice (−0.1 %) (Lobell et al. 2011). However, it is interesting that, except for maize, these decreases have been attenuated/canceled following the CO_2 atmospheric fertilization, which determined increases of ~3 % in wheat, soy and rice yields over the ~30 years (considering that the atmospheric CO_2 concentration increased in this period by 47 ppm, and every ppm determined yield increases for the three cultures by ~0.065 %) (Ainsworth et al. 2008; Lobell et al. 2011).

In the study area, the high warming rates in the growing seasons of maize or wheat, as well as in the key-seasons of spring and summer, indirectly highlight an increasingly high pressure trend on water resources in the last decades, due to evapotranspiration acceleration. This hypothesis is confirmed by a national-scale study on reference evapotranspiration trends in the 1961–2007 period, in which high evapotranspiration rates were found, with peak punctual values (especially in southern Romania) of 11 mm/decade in spring, 13 mm/decade in summer, 19 mm/decade in the growing seasons of maize and wheat, and 25 mm/decade on the annual scale (Croitoru et al. 2013a).

However, with regard to national/regional studies, there are no approaches on quantifying the climate change impact on agricultural yields (from the perspective of changes in temperature, but also in evapotranspiration and precipitation) by means of statistical models. Through its case study, applied for the 1991–2000 period, the study attempted to obtain new results and to confirm the hypothesis regarding the impact of climate warming on agricultural production at large spatial scale. However, it is important that the results be interpreted cautiously, given the relatively limited data samples. Also, although the statistical results showed high maize yield losses for a 1 °C temperature increase, it is noteworthy that regressions are significant at the threshold below 0.05 in less than half of cases. This is due to other variables possibly influencing maize crop dynamics (which were not included in the present analysis), either climatic (e.g., minimum and maximum temperatures, rainfall), or non-climatic (e.g., agricultural system management) variables.

Quantifying the response of maize crops to temperature changes in the study area is even more difficult in the context of the socio-political transition occurring after 1990, which determined major changes in agricultural management (collapse of irrigation systems, excessive parceling of agricultural terrain, reduction of fertilizer quantities etc.), against the background of property type changes, decline of state support for agricultural production, migration of population from rural areas etc. (Lakes et al. 2009; Bălteanu et al. 2013; Prăvălie et al. 2014b). Considering all these additional factors, which were not integrated in the regression model in the present study (due to the study's aim and to the general lack of detailed administrative data), it can therefore be concluded that the results of the climate-agriculture analysis are surprising, considering the generally close statistical relationships obtained solely based on temperature as predictor variable.

Moreover, a limitation of the study may also be related to the fact that, when approaching the temperature—maize relationships, the more advanced statistical models, common in specialized literature (Lobell and Field 2007), were not used, mainly due to the limited data (these models generally require time series of at least 25–30 years). However, the method provides satisfactory results for smaller data sets (considering other climate data than temperature), as shown in other regional studies conducted in south-western and south-eastern Romania (Prăvălie et al. 2014b, 2016).

4.3 Negative consequences of climate warming on regional ecological systems

In addition to anthropogenic (agricultural) systems, another vulnerable component to climate warming consists of regional ecosystems. The most important are the wetland (especially the Danube Delta) and forest ecosystems.

The Danube Delta, although it only covers 5.5 % of the study area ($\sim$3500 km^2 in the Romanian sector) (Gâstescu and Posea 2005), is the most complex local system and has, at the same time, major global importance due to its being a biodiversity hotspot (it brings together approximately 2000 species of plants and 5000 fauna species) (Giosan et al. 2014). Its universal value is also due to the fact that it is the most compact reed area in the world, the largest continuous marshland in Europa and the most extensive in the European Union (Giosan et al. 2014; PRDD 2014). Through the ecosystem services it provides (provisioning, regulating, supporting and cultural services), similarly to other major wetlands (MEA 2005), the Danube Delta constitutes an essential support to human well-being.

In the context of the climate warming of the last three decades, it is estimated that there already is significant pressure on natural systems. A series of negative effects was therefore reported, such as less snow in winter, evapotranspiration increases (and, implicitly, climatic water deficit increases), sea level rise (and, as a result, flooding and erosion risk in coast areas), higher temperatures of water bodies, phenological changes in plants, fish species reproduction disruption etc. (Bandoc 2008, 2012; Dan et al. 2009; Syvitski et al. 2009; Bandoc and Golumbeanu 2010; Bandoc et al. 2013, 2014; Kovbasko et al. 2014). In the future, against the background of climate warming, it is estimated that all these negative environmental effects will escalate (Kovbasko et al. 2014).

Another major impact of climate warming on ecological systems consists in forest species withering. Although they cover a considerable area, i.e., $\sim$4000 km^2 (more than 6 % of the total area, mostly in the center, west and north-east) (CLC 2006), there are currently very few studies on climate change impact on the structure and functionality of these ecosystems in southern and south-eastern Romania.

However, certain current studies performed in the south-western sector of the study area showed, by means of teledetection techniques, the withering of forest species in extensive areas, due to the thermal stress generated by high air temperatures (Prăvălie et al. 2014a, c). Forest ecosystem service deterioration was therefore identified, and this has destabilized the fragile balance of environmental systems in this southwestern area, known country-wide for its advanced state of land degradation (Peptenatu et al. 2013; Stringer and Harris 2014).

5 Conclusions

This paper generally analyzed the direction and magnitude of multiannual and multidecadal mean air temperature trends in Romania's most important agricultural area, the southern and south-eastern regions, based on climate data recorded between 1961 and 2009 at 23 weather stations, uniformly distributed in the study area. By means of widely used methods in specialized literature (the Mann–Kendall test, the Sen's slope method and linear regression), the following results were obtained:

(1) statistically significant multiannual climate warming on all temporal scales, except for autumn, which presents cooling with no statistical significance; this corresponds to the air temperature trend pattern, identified annually and seasonally by specialized studies carried out in Romania;

(2) the most intense warming trends were found in summer, in terms of magnitude (peak rates of 0.058 °C/year, net warming of almost 3 °C) and statistical significance (100 % significant trends, of which $\sim$80 % at the $\alpha = 0.001$ threshold); this aspect highlights that this season's temperature dynamics has the highest contribution to the annual warming;

(3) pronounced multidecadal dynamics, characterized by two instances, i.e., general climate cooling in the 1961–1990 period and warming in the 1971–2000/1981–2009 period;

(4) significant cooling in autumn in the 1961–1990 period, 96 % statistically significant (with a maximum value of -0.07 °C/year, or exceeding 2 °C net cooling); therefore, this three-decade period influenced the climate cooling trend to the highest extent in autumn, throughout the entire analysed period, 1961–2009;

(5) while the 1971–2000 period stands out in terms of positive temperature trends, they are generally not statistically significant, with two notable exceptions, i.e., summer (positive rates of up to 0.094 °C/year, almost 3 °C total warming) and maize growing season; the lack of significance in the other cases indicates a transition trend pattern, from general cooling, identified in the first three decades, to significant warming in the 1981–2009 period;

(6) the period of the past three decades shows a general warming (maximum in summer, with extreme values of 0.092 °C/year, or more than 2.5 °C net warming), uniform on all seven temporal scales (including in autumn, when warming trends are significant in approximately 40 % of cases); this period stands out in terms of the highest temperature increase rates, considering spatial average magnitude and trend significance (thus proving the fact that climate warming is still currently ongoing, with an increasingly higher intensity);

(7) the 1991–2000 case study on the relationship between climate and crops showed that agricultural systems are vulnerable to a considerable extent to the significant warming of the past three decades; for maize crops, it was noticed that, in 83 % of the total study area, a 1 °C temperature increase determined high yield losses, generally exceeding 1 t/ha/year (considering p value <0.1); considering p value <0.05, in order to ensure more rigorous statistical results, it was noticed that in 32 % of the study area climate warming accounted for up to 50 % of maize crop variation, causing maximum losses of 1.5 t/ha/year for a 1 °C temperature increase; all these agro-climatic results must however be regarded with caution, considering the relatively short time interval of the analysed case study.

Therefore, while in terms of multiannual direction, the climatic results confirm the overall global state of temperature dynamics, in terms of magnitude, climate warming has, for the most part, different values. For instance, considering the mean annual warming in the past half-century identified in the study area (0.22 °C/decade), it is almost twice as high as the global trend (0.13 °C/decade) (IPCC 2007). At European scale, this almost double warming rate corresponds to a pattern followed by many countries on the continent, such as Spain (del Rio et al. 2011), Italy (Toreti and Desiato 2008), Slovenia (de Luis et al. 2014), Croatia (Pandžic and Likso 2010), or Poland (Degirmendžić et al. 2004). At the same time, agro-climatic results confirm the issue of the negative impact of climate change on agricultural systems, signalled on numerous other cases, in Europe and worldwide.

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