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Inter-annual variability and trends of the frost-free season characteristics over Central and Southeast Europe in 1950-2019

Многогодишна изменчивост и тренд на характеристиките на безмразовия период над Централна и Югоизточна Европа през 1950-2019

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ABSTRACT

Agriculture and forestry are two economic sectors most dependent on climate, and climate change has a direct and indirect impact on biotic and abiotic disturbances with strong implications. The air temperature is one of the major environmental factors affecting growth, development, and yields of crops. Despite the undeniable global warming, damage to crops by frost and freezing temperatures causes serious loss to farmers in many parts of the world. The frost-free season has a large influence on plant phenology, with implications for the distribution of natural vegetation and the types of crops grown in a particular region. The present study is dedicated to the climatology of the frost-free season over Central and Southeast Europe in the second half of the previous and the first two decades of this century. The climatology of the frost-free season is characterized by three indicators, namely the date of the last spring frost, the date of the first autumn frost, and the length of the frost-free season. Additionally, the middle date of the frost-free season as measure of the seasonal shift is analysed. The study, which is performed for the thresholds of -2.2 °C and 0 °C, reveals non-negligible lengthening of the frost-free season, associated primarily with an earlier date of last spring frost rather than a delayed date of first autumn frost.

Keywords: climate change, frost-free season, last spring frost, first autumn frost, E-OBS

РЕЗЮМЕ

Селското стопанство и лесовъдството са икономическите сектори, които са най-зависими от климата и климатичните промени имат пряко и непряко влияние върху биотичните и абиотични смущения със съществени последствия. Температурата на въздуха е един от главните екологични фактори, въздействащи на растежа, развитието и продуктивността на селскостопанските култури. Независимо от неоспоримото глобално затопляне, щетите върху културите от мраз и отрицателни температури предизвикват сериозни загуби на фермерите в много части на света. Безмразовият период оказва съществено влияние върху фенологията на растенията, има отношение към разпределението на естествената растителност, както и вида на селскостопанските култури, растящи в даден район. Представеното изследване е посветено на климатологията на безмразовия период над Централна и Югоизточна Европа през втората половина на миналия и първите две десетилетия на настоящия век. Тази климатология се характеризира посредством три индикатора, а именно датата на последния пролетен мраз, датата на първия есенен мраз и дължината на безмразовия период. В допълнение е анализирана и датата на средата на безмразовия период, която е показател за сезонното отместване. Изследването, което е проведено за двете прагови стойности -2.2 °C и 0 °C, разкрива съществено удължаване на безмразовия период, което се дължи в по-голяма степен на по-ранното настъпване на последния пролетен мраз, отколкото на по-късното настъпване на първия есенен мраз.

Ключови думи: климатични промени, безмразов период, последен пролетен мраз, първи есенен мраз, E-OBS

INTRODUCTION

According to the recently published contribution of the Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021), the scale of recent change across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years. Regional climatic change over Central and Southeast (CSE) Europe associated with global warming have been the subject of many in-depth studies using data from various sources (Alexander, 2006; Bartholy and Pongracz, 2006, 2014; Chervenkov and Slavov, 2019, 2020; Cheval et al., 2014; Lakatos et al., 2016; Lavaysse et al., 2017). Most of these studies which consider the second half of the 20th and the first decade of the 21st century, clearly evidence that, similarly to the global and continental trends, the regional temperature has got higher.

Among other sectors, agriculture and forestry are evidently most dependent on climate and climate change has a direct and indirect impact on biotic and abiotic disturbances with strong implications (Menzel et al., 2006; Vitasse et al., 2014). Crops and livestock are directly impacted by adverse local weather and climate (Hatfield and Prueger, 2011, 2015; Seemann et al., 1979). Associated to climate change, there are several factors affecting agricultural ecosystems that may act independently or in combination (Harkness et al., 2020). Temperature is one of the major environmental factors affecting growth, development, and yields of crops (Luo, 2011). Apart from the link between the variability of the mean temperature and the seasonal development of plants, extreme events are also significant to phenology. A combination of early spring warming with succeeding low-temperature events, for example, can be detrimental to plant and animal species living on the margin of their climatic range (Scheifinger et al., 2003). Changes in thermal conditions may also have adverse effects such as the development of thermophilic weeds, pests, or the emergence of new plant diseases.

The modelling of frost risk is complex as the damage depends on crop variety, planting, and harvest dates as well as many other factors. In addition to temperature, the duration of freezing temperatures is also important in determining the damage that occurs. The longer the duration, the greater the chance of ice-nucleation to occur, and the greater spread of ice-nucleation through the ear and subsequent plant damage (Barlow et al., 2015). The frost-free season (FFS), defined as the period between the last spring frost and the first autumn frost, has a large influence on plant phenology, with implications to the distribution of natural vegetation and the types of crops grown in a particular region (Menzel et al., 2003; Vitasse et al., 2014). Changes in the length of the FFS may alter not only agricultural productivity and practices, but also the function and structure of regional ecosystems (Zhong et al., 2017). In the last decades a few studies document changes in frost days (see Easterling, 2002; Wypych et al., 2017 and references therein). Most of them are based on phenological evidences or on analyses of temperature records. The thermal impact of the frost could be quantified by various agrometeorological (AM) indicators (Harding et al., 2015). The most widely used indicators are based on single-value thresholds of daily minimum air temperature, hereafter referred to as tn (Menzel et al., 2003). The aim of the present study is to estimate the long-term spatial and temporal variability as well as the timing of the FFS. The characteristics of the FFS are quantified with a set of indicators including the days of the year of the last spring frost (LSF), first autumn frost (FAF), and the length of the FFS. All these characteristics are economically important and are studied extensively in Europe and worldwide. Researchers generally agree that global trends of rising air temperatures are reflected in the reduction of the number of frost days and in the lengthening of the FFS. In Europe, there is practically no region in which the described changes would not be observed (Wypych et al., 2017). The timing of the FFS is estimated by means of the middle day of the period, noted subsequently MFS. Similar to the proposal of Wypych et al. (2017), the analysis is also performed for the threshold of -2.2 °C, which is important for cold-tolerant cultivars.

The importance of assessing long-term variability of the analyzed variables is frequently emphasized (Alexander et al., 2006; Bartholy and Pongracz, 2006; Chervenkov and Slavov, 2019). The primary reason for this is to estimate the sustainability of the detected inter-annual changes.

The present study is a continuation of our recent efforts, dedicated on another important AM indicator, the thermal growing season (TGS) (Chervenkov and Slavov 2019, 2021a, 2021b), and fits in the same conceptual framework.

DATA, METHODS AND PERFORMED CALCULATIONS

The gridded daily dataset E-OBS, which is popular in the expert community, has been developed primarily for regional climate model evaluation, but it is also used subsequently for various applications. As it has been demonstrated in Chervenkov and Slavov, (2019), E-OBS is a suitable product for the computation of climate indices. Data for tn from E-OBS v10.0 at 0.25° spatial resolution are used in Wypych et al. (2017) for assessment of spatial and temporal variability of the frost-free season in Central Europe. As temperature extremes are highly sensitive to local conditions, gridded data have the tendency to underestimate the tails of the distribution. It is especially significant in low temperatures, so that over-smoothing is stronger in wintertime and may also influence the number of spring and autumn frost days (Scheifinger et al., 2003; Wypych et al., 2017). In addition to improved uncertainty quantification, the ensemble versions of E- OBS (i.e. v16.0e and later, Cornes et al., 2018) generally represent temperature extremes better than their predecessors.

In the present study, the analysis was performed for the period 1950–2019 using tn-values from E-OBS v.21.0e over CSE Europe with a spatial resolution of 0.1°×0.1°. Any day on which minimum air temperatures dropped below 0°C was classified as a day with frost. Additionally, to assess the possible impact of temperature variability on plant development, severe frost events tn<−2.2°C (WMO, 1963; Wypych et al., 2017) were also examined. Following Easterling (2002), frost occurring before the day of year (DOY) 182/183 (i.e. 1th July) is considered a spring frost event, and that occurring on or after 1 July is considered an autumn frost event. Furthermore, if no frost occurs on any day in the first or second half of the year, frost-free indicators are not calculated. For each year studied, dates of the LSF and FAF were extracted from the data set and the resulting MFS and FFS length was calculated for each grid point separately. According to the original proposal (Chervenkov and Slavov, 2021b) for the case of the TGS, the middle day of the frost-free season MFS, where MFS=(LSF+FAF)/2, is an indicator of the seasonal shift which is independent of the FFS length. If the MFS tends in its inter-annual course to happen earlier, this indicates a negative seasonal shift of the whole FFS. Conversely, MFS on later dates marks a positive seasonal shift of the FFS.

In order to assess the long-term inter-annual change, the multi-year means (MM) of the LSF, MFS, FAF, and the FFS length for the first 30 years, i.e. 1950-1979 are analyzed in parallel with those for the last 30 years, i.e. 1990-2019. The absolute difference of the MM for the second period in respect to the first is applied as a measure of the long-term change.

In the present work, the magnitude of the trend is estimated with the Theil-Sen Estimator (TSE) and its statistical significance is analyzed with the Mann-Kendall (MK) test. The TSE and the MK test are procedures that are particularly suitable for non-normally distributed data, data containing outliers and non-linear trends. Consequently, they are widely used in many engineering and geophysical branches as hydrology, hydro-geology and meteorology. They are recommended from the World Meteorological Organisation (WMO, 2000) and are practically standard tools for statistical assessment of trend in the climatology (Chervenkov and Slavov 2020, 2021a, 2021b; Cheval et al., 2014; Lakatos et al., 2016).

RESULTS AND DISCUSSION

The observed increase in air temperature in the northern hemisphere in recent decades is undeniable, especially in Europe (Alexander et al., 2006; IPCC, 2021). The magnitude of changes impacts strongly the temperature trend in the transitional seasons, which was the most relevant time period for this study (Cheval et al., 2014; Lakatos et al., 2016; Wypych et al., 2017). Figure 1 demonstrates the regional implication of the hemispheric and continental tendencies. The multiyear monthly mean tn is computed for both periods, 1950-1979 and 1980-2019. The areal averaged (AA) over the whole domain values of these means for both periods are shown in Figure 1 where regional warming is demonstrating as the red line is above the blue one in the bigger part of the year.

The comparison of the MM of the LSF, MFS, FAF, and the FFS length is performed for both thresholds of 0 °C and -2.2 °C separately and the results are shown in Figures 2 and 3, respectively. With the intention of making the comparison of both figures easier, the same color legend is used.

Many conclusions could be outdrawn from Figure 1 but the first and most noticeable one is the clear spatial structure of all of the considered indicators. As in the case of the TGS (Chervenkov, and Slavov, 2019, 2021b), the vertical gradients are better expressed than the horizontal ones. As expected, the LSF is earlier and FAF is later in the regions with generally warmer climate – the southern coastal areas. In Wypych et al., (2017) is also emphasized that the longest minimum temperature above 0 °C remains in coastal regions, in particular on the Black Sea coast. The FFS is shortest in both considered periods over the NW part of the domain and especially over the mountains, most prominent over the main Carpathian ridge. It is worth emphasizing the minor importance of the latter from an agricultural point of view. Over part of Romania, Slovakia, the Czech Republic, and Poland the minimum air temperature below 0 °C persists after DOY=120, i.e. after the end of April. The DOY FAF appears more evenly distributed – over the bigger part of the domain is typically in the range 290-310, i.e. in the second half of October. As a result, the FFS lasts the longest, more than 250 days, over relatively small regions near the coast in Greece and Turkey. Most of the area is characterized by FFS persisting 200-210 days. The spatial distributions for the second period are generally consistent with their counterparts for the first period. There are no, at least apparent, principal changes. The maps of the absolute differences show, first of all, that the FFS has become significantly prolonged (more than 2 weeks) over the bigger part of the domain. More significant is the increase over the western half, but without clear spatial structure. The analysis of the maps of the LSF, FAF, and especially MFS shows, that this prolongation is due to earlier LSF, rather than later FAF.

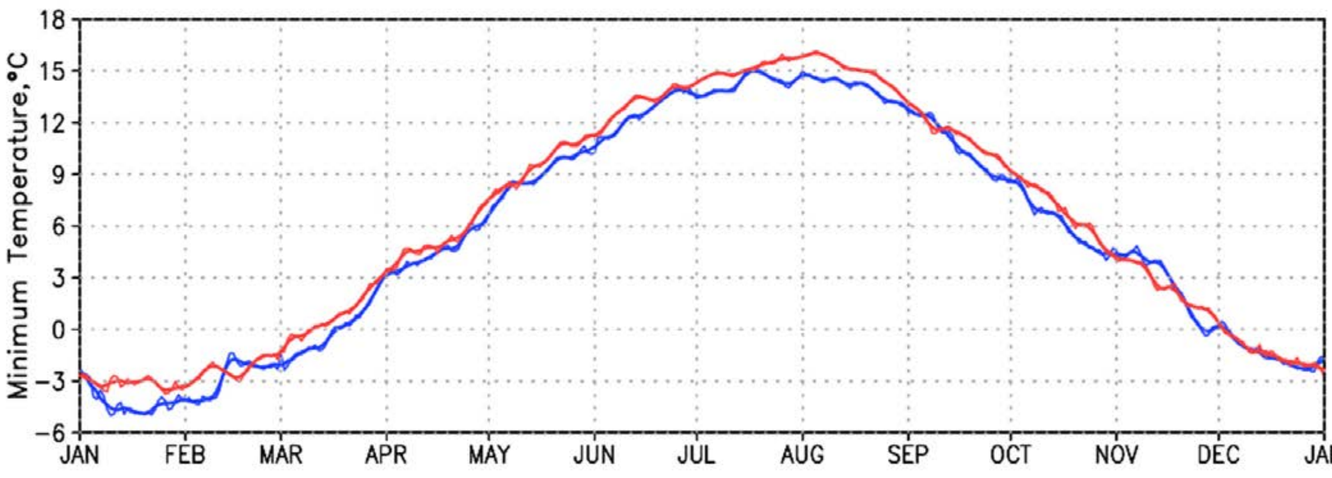

Figure 1. AA multiyear intra-annual cycle of the minimum temperature (units: °C) for 1950-1979 (blue line) and the same for 1980-2019 (red line). Bold lines are the centred 5-year moving averages

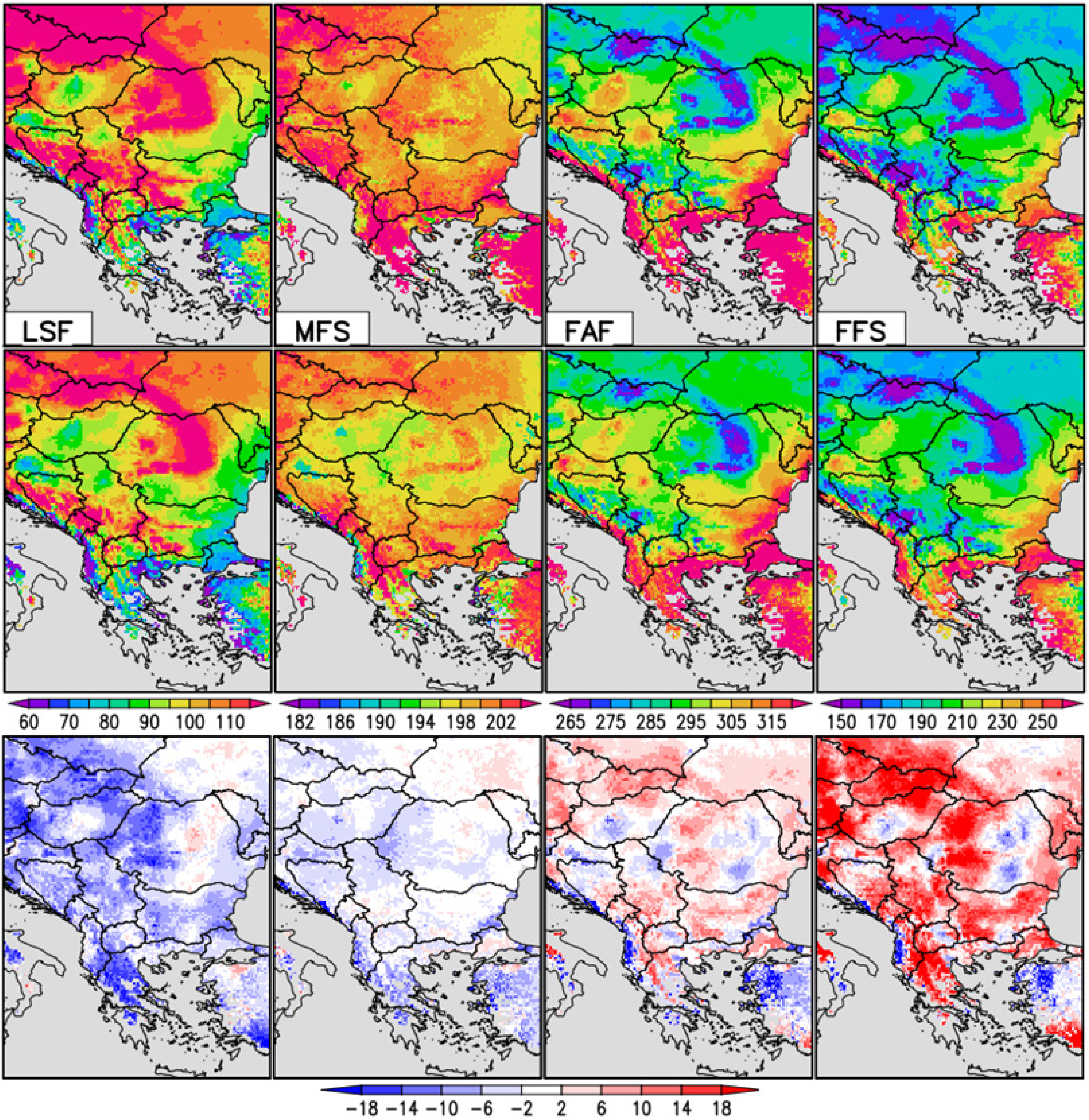

Figure 2. MM of the considered indicators according the subplot titles for the threshold of 0 °C for the period 1950-1979 in the first and for 1990-2019 in the second row. The differences are shown in the third row. The units are DOYs for LSF, MFS, FAF and days for FFS and for the absolute difference

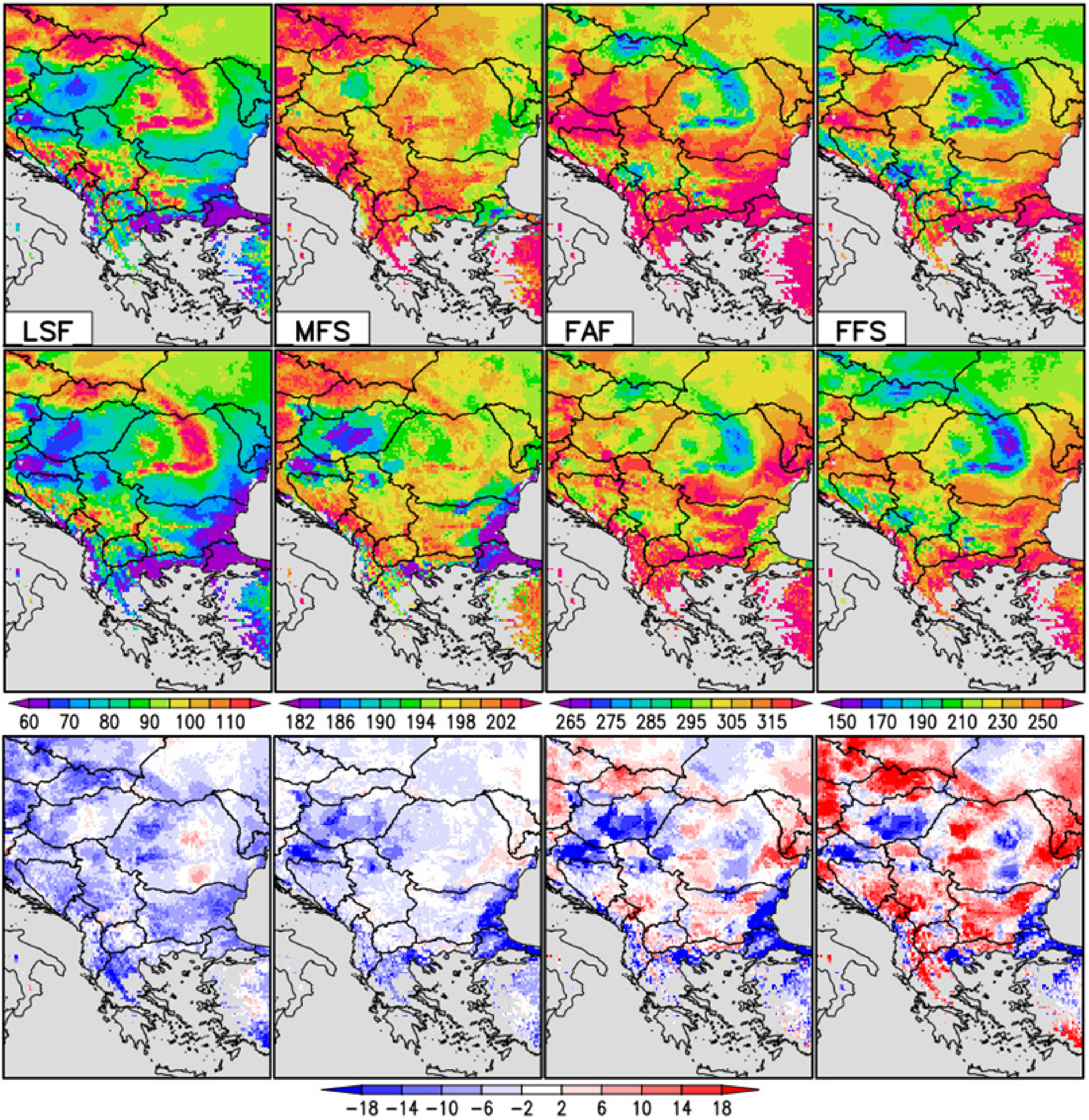

Figure 3. MM of the considered indicators according the subplot titles for the threshold of -2.2 °C for the period 1950-1979 in the first and for 1990-2019 in the second row. The differences are shown in the third row. The units are DOYs for LSF, MFS, FAF and days for FFS and for the absolute difference

This result is in accordance with the outcomes in Scheifinger et al. (2003). One of the key messages in the latter study is that frost events based on the last occurrence of daily minimum temperatures have been moving faster to earlier occurrence dates than phenological phases during the last decades at 50 climate stations in Central Europe.

There are also relatively small, scattered, and isolated regions, with a reduction of the FFS length. Some of them, for example over Romania, could be explained with a problematic representation of the tn in E-OBS there.

The northern margin of the considered domain in this study overlaps with the southern part of the domain in Wypych et al. (2017). Although the observed period in the latter is 1951-2010, the obtained values in both studies for LSF, FAF, and FFS length are generally identical.

The threshold for severe frost -2.2 °C is recommended by WMO which motivates our choice.

The overall impression of the spatial distributions of the considered indicators in Figure 3 is that there is no principal disagreement with the picture in Figure 2. Due to the lower threshold, the LSF occurs earlier and the FAF later over the same places compared with the threshold of 0 °C. As a result and as expected, the FFS length for the lower threshold is longer everywhere. The absence of computed values of the considered indicators over south Italy and Greece as well as east Turkey suggests that, according to the applied methodology, there is no upwards and downwards transition trough -2.2 °C, most probably the tn remains above this threshold the whole year round. This indicator, similarly to some climate indices (Alexander et al., 2006), is not meaningful for the maritime Mediterranean climate. The maps of the absolute differences show generally similar behavior as their counterparts for the threshold of 0 °C. The spatial inhomogeneities are better expressed. It is worth emphasizing that in Hungary, Croatia, and the Black Sea regions of Bulgaria and Turkey, the FAF occurs in the second period more than two weeks earlier, in contrast to the main tendency.

Since the long-term inter-annual change of the parameters of the FFS are in the focus of our study, their temporal evolution should also be considered. Figure 4 shows the time series of the AA over the whole domain of the LSF, MFS, FAF, and FFS length for both temperature thresholds.

The most important result of the analysis of Figure 4 is the increasing course of FFS length for both temperature thresholds, especially noticeable after the eighties.

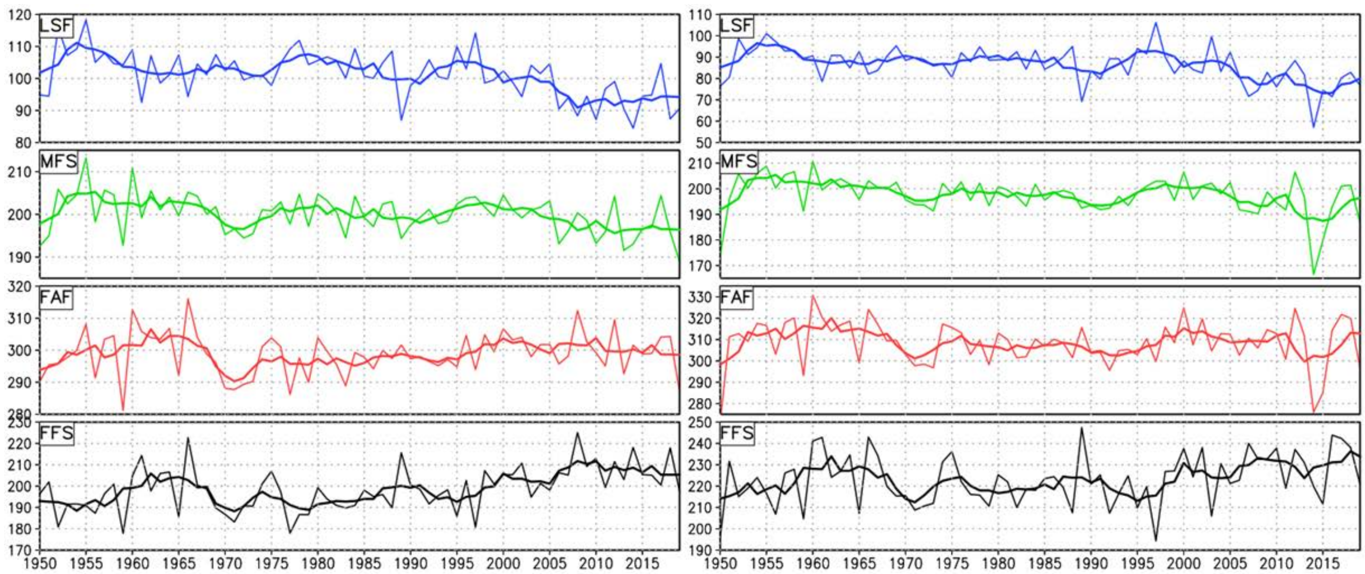

Figure 4. Temporal evolution of the AA of the considered indicators according the subplot titles for the threshold of 0 °C (left column) and for the threshold -2.2 °C (right column). Bold lines are the centered 5-year moving averages

The downward and upward tendency of the LSF and FAF, respectively, could also be noted, although they are not as obvious.

The FFS and LSF and FAF dates are characterized by large fluctuations from year to year. This fact is also noted in Wypych et al. (2017).

Recently, a few studies document the prolongation of the TGS over CSE Europe (Chervenkov and Slavov, 2020, 2021a, 2021b; Cheval et al., 2014; Lakatos et al., 2016). Consequently, significant trends in the seasonal behavior of plants and animals have unequivocally been observed in many regions of the world during the last decades (Scheifinger et al., 2002, 2003). The length of the vegetation period of many plant species has been increasing through an advanced onset of spring phases and a forward shift of autumn phases in midlatitudes (Menzel et al., 2003, 2006).

The results from the trend analysis of the FFS-related measures are shown in Figure 5. Traditionally, (Chervenkov and Slavov 2021a, 2021b; Cheval et al., 2014; Lakatos et al., 2016) the results were evaluated at the significance levels of 5%.

The trend analysis is performed only for these grid cells which time series consists only of defined values. Thus, the grayed areas over the land, clearly apparent over Italy, Greece, Turkey, and Bulgaria, indicate indirectly that there FFS indicators cannot be calculated at least in one year. Obviously, these areas are bigger for the lower threshold (the second row of Figure 5). Changes in FFS length are as a result of spatial trends in LSF and FAF. The prevailing trend of the FFS length is positive, especially for the upper threshold. It is statistically significant over many scattered places, more noticeable and compact over the NW part of the domain where the negative trend of the

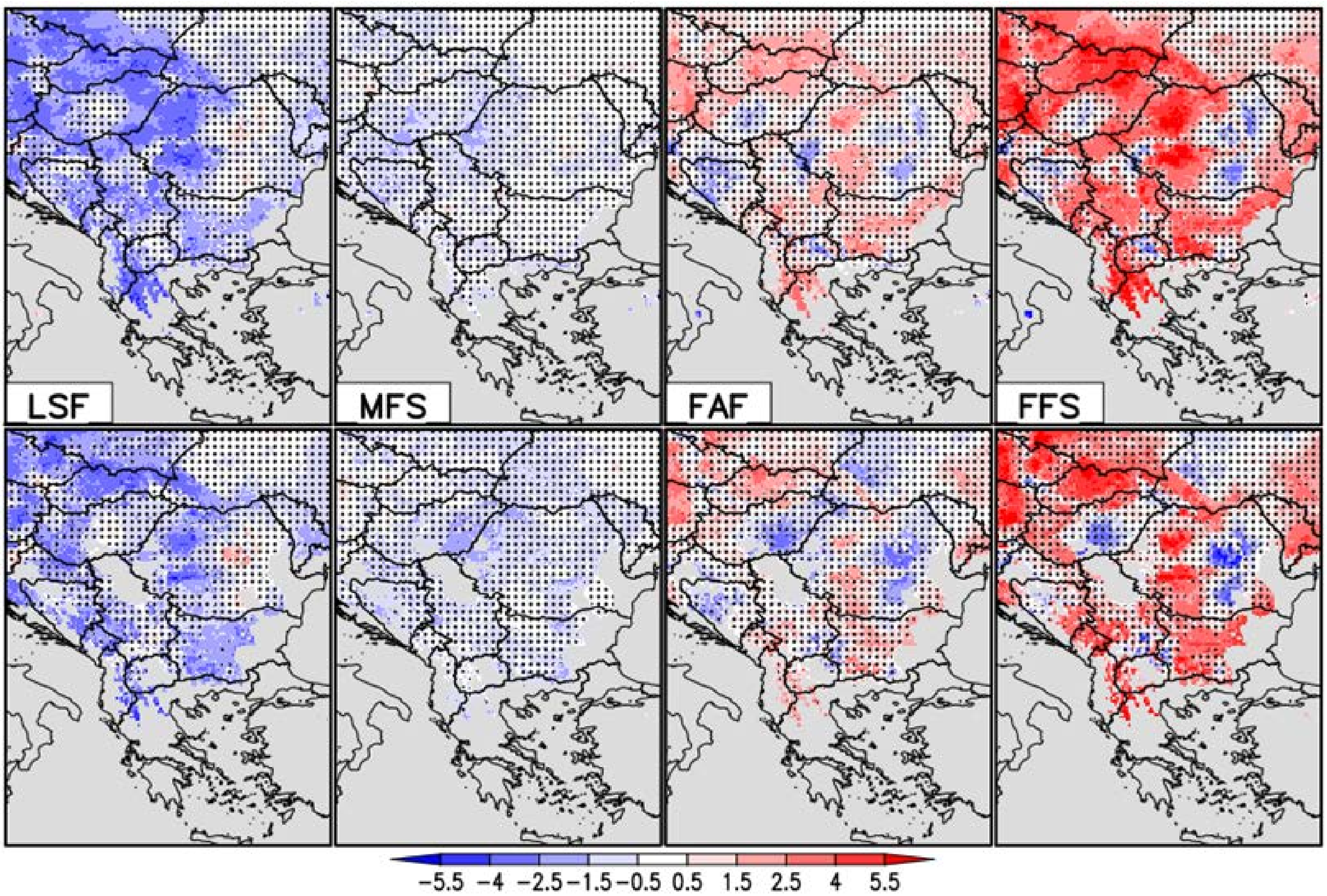

Figure 5. Trend magnitude (unit: days per 10 years) of the considered indicators according the subplot titles for the threshold of 0 °C (first row) and for the threshold of -2.2 °C (second row). Stippling indicates grid points with changes that are **not** significant at the 5% significance level

LSF is also significant. In turn, the trends of MFS and FAF are not practically significant everywhere. The magnitude of the positive trend over part of Romania and even more clear over Slovakia is typically in the range of 4 to 6 days over 10 years and the negative trend of the LSF in the same region is -6 to -4 days over 10 years. These values are very close to the results of Wypych et al. (2017). Evidently, the prolongation of the FFS is linked more to the earlier occurrence of LSF rather than the latter of FAF. It is worth mentioning, however, that this seasonal shift is, as shown on the subplot of the MFS, statistically not significant. It (Menzel et al., 2003) is also stressed that the respective findings for the mean temperature ≥ 7 °C clearly deviate from those for the other analyzed thresholds. This main outcome agrees in principle with the results of some studies for the mid- and higher latitudes of the Northern Hemisphere revealed from different data sets, such as station network measurements, assimilated data, and phenological 'ground truth' (Menzel et al., 2003, 2006; Scheifinger et al., 2002, 2003; Vitasse et al., 2014; Wypych et al., 2017).

Despite a significant decline in the number of days with frost, the risk associated with the occurrence of frost, mainly in spring, remains a serious problem, especially in the northern half of the studied domain, where the continentality of the climate is well expressed.

CONCLUSION

Based on the availability of up-to-date data, we present an analysis of the characteristics of the frost-free season over CSE Europe for the second half of the 20th and the first two decades of the 21st century. To determine the FFS, we used two single-value thresholds of the minimum temperature: -2.2 °C and 0 °C. Although not exhaustive, the study gives clear evidence of the lengthening (although with significant spatial inhomogeneities) of the FFS. This main outcome is in principal agreement with the consolidated results of most recent investigations for other parts of Europe. It should be noted that such regional studies for the considered domain of CSE Europe are scarce. Another key message from the presented study is that the total lengthening of the FFS is caused mainly by the earlier occurrence of the LSF, rather to the latter of the FAF. Generally, these results are similar to our findings outdrawn from the analysis of the TGS. This result is not trivial, hence the warming is different for the minimum, mean, and maximum temperature (warming asymmetry) which reflects on the long-term tendencies of the climate indicators based upon them. Although minimal, the obtained differences of the trends of the FFS for both thresholds should be noted.

Despite our findings, the early autumn frost and, more importantly, the early spring frost remain problematic from an agricultural perspective. The earlier timing of phenological events due to rising air temperatures could favour the occurrence of more damaging spring frost events because of the closer timing of some phenophases.

A research focus of follow-up work could be more complex approach, using, for example multiple, rather single-value thresholds since the latter could be sometimes misleading.

The estimated changes of FFS-related indicators could be a necessity for deep ecological and economic consequences. They are likely to accelerate in the future with the projected generally warmer climate. Subsequently, similar studies could be the methodologically reliable scientific basis of the long-range policy and expert assessments for managing systems as agriculture and forestry.

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