SOIL MOISTURE TRENDS IN THE CZECH REPUBLIC BETWEEN 1961 AND 2012 - ARE DROUGHTS MORE LIKELY?

MIROSLAV TRNKA[1,2*], RUDOLF BRÁZDIL[2,3], JAN BALEK[1], DANIELA SEMERÁDOVÁ[2], PETR HLAVINKA[1,2], MARTIN MOŽNÝ[1,4], PETR ŠTĚPÁNEK[2,5], PETR DOBROVOLNÝ[2,3], PAVEL ZAHRADNÍČEK[2,5], MARTIN DUBROVSKÝ[2,6], JOSEF EITZINGER[2,7], BRIAN FUCHS[8], MARK SVOBODA[8], MIKE HAYES[8], ZDENĚK ŽALUD[1,2]

[1]*Department of Agrosystems and Bioclimatology, Faculty of Agronomy, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic*
[2]*Global Change Research Centre AS CR, v. v. i. Bělidla 986/4a, 603 00 Brno, Czech Republic*
[3]*Department of Geography, Masaryk University, Kotlářská 267/2, 611 37 Brno, Czech Republic*
[4]*Czech Hydrometeorological Institute, Doksany Observatory, Doksany 105, 411 82 Doksany, Czech Republic*
[5]*Czech Hydrometeorological Institute, Brno Regional Office, Kroftova 43, 616 67 Brno, Czech Republic*
[6]*Institute of Atmospheric Physics, Czech Academy of Sciences, Boční II/1401, 141 31 Prague, Czech Republic*
[7]*Institute of Meteorology, University of Natural Resources and Life Sciences (BOKU), Peter-Jordan-Straße 82, 1190 Vienna, Austria*
[8]*National Drought Mitigation Center, University of Nebraska-Lincoln, 3310 Holdrege Street, Lincoln, NE 68583, USA*

Soil moisture dynamics and their temporal trends in the Czech Republic are forced by various drivers. Our analysis of temporal trends indicates that shifts in drought severity between 1961 and 2012 and especially in the April, May, and June period, which e.g. displayed a 50 % increase in drought probability when 1961–1980 and 2001-2012 is compared. We found that increased global radiation and air temperature together with decreased relative humidity (all statistically significant with P < 0.05) led to increases in the reference evapotranspiration in all months of the growing season; this trend was particularly evident in April, May, and August, when more than 80 % of the territory displayed an increased demand for soil water. These changes, in combination with the earlier end of snow cover and the earlier start of the growing season (up to 20 days in some regions), led to an increased actual evapotranspiration at the start of growing season that tended to deplete the soil moisture earlier, leaving the soil more exposed to the impacts of rainfall variability. These results support concerns related to the potentially increased severity of drought events in Central Europe. The reported trend patterns are of particular importance with respect to the expected climate change, given the robustness and consistency of the trends shown and the fact that they can be aligned with the existing climate model projections.

Keywords: drought, soil-moisture, SoilClim, monitoring

INTRODUCTION

After floods, droughts represent the most disastrous natural events in the Czech Republic (Brázdil *et al*., 2007). A study by Brázdil *et al.* (2013) analyzed droughts in the Czech lands between AD 1090 and 2012 based on documentary and instrumental data and concluded that despite great variability since 1501, the frequency of drought occurrence since the 1990s is particularly noteworthy. While the severe droughts of the 19th century occurred in a relatively cooler climate and were caused by lack of precipitation, more recent droughts in the Czech Republic have been primarily driven by increasing reference evapotranspiration (i.e., potential water requirements) rather than any important decrease in precipitation totals (Brázdil *et al*., 2012 and Brazdil and Trnka *et al.,* 2015). The concerns were strengthened recently by Trnka *et al.* (2014, 2015), who confirmed significant shifts in drought severity in the 1961–2012 period over the territory of the Czech Republic using newly available high-resolution climate datasets. Although no statistically significant trends in precipitation were noted during the 1961–2012 period (Brázdil *et al*., 2012), statistically significant trends toward lower soil moisture content were observed, most notably during the May–June period. This study explores the causes of the change in the modeled soil moisture content in the Czech Republic in 1961–2012, including how it compares with newly available observations and to what extent these changes agree with larger-scale assessments.

MATERIALS AND METHODS

The principal method used to determine drought (described in detail by Trnka *et al.,* 2014, 2015) relies on an analysis of the daily root-zone soil moisture content (up to 1.3 m or the maximum rooting depth). This value was calculated for each 500 m grid using the SoilClim model based on the Allen *et al.* (1998) model, which was partially modified by Hlavinka *et al.* (2011). SoilClim applies the Penman-Monteith method to estimate the reference evapotranspiration and accounts for other factors that affect soil moisture, including soil water holding capacity, phenophase development, root growth, and snow cover accumulation/melting. The snow cover is estimated based on the daily maximum and minimum temperatures and the precipitation totals using the SnowMAUS model, which was validated for the Central European region by Trnka *et al.* (2010). To account for the effects of horizon obstruction, slope, and aspect, the sum of the daily global radiation value in each grid was modified using an approach described by Schaumberger (2011). The soil data were based on the work of Trnka *et al.* (2015). The land cover information relied on the Corine land cover (CLC2006) with a resolution of 100 m (version 12/2009), and no calculations were performed over urbanized areas (7.0 %) and water bodies (1.1 %). The whole system was repeatedly validated with results being presented by Hlavinka *et al.*,2011 and Trnka *et al.* (2014, 2015)

The significance of trends was assessed using Spearman's rank correlation coefficient and was tested by regression analysis using a 0.05 significance level. To avoid the existing autocorrelation that is intrinsic to some of the analyzed data (e.g., snow cover or phenophases), the trends were separately evaluated for individual months or periods. In this manner, all parameters can be considered independent.

RESULTS

As Fig. 1e-f indicates, most of the Czech Republic exhibits a tendency toward decreasing soil water content and it is true especially between April and September. The areas with the most pronounced drying trend are located in the most productive agricultural areas. The drying trends are strongest in May, with 44.1 % of all grids exhibiting statistically significant decreasing soil water content in the entire profile, closely followed by June (36.4 %). In other months, the drought trends are much less pronounced. Changes in the May soil water content are of particular importance because the soil moisture content during this month plays a significant role in determining agricultural and forestry production. June is the second-most important month in this respect. The negative soil moisture trends are most pronounced in grids with grasslands and meadows and May has the strongest drying trends, with more than 83 % of grassland grids affected. This is well depicted in Figs. 1e–f, which show a prevailing trend toward lower soil water content, particularly during the April–June (AMJ) period. This trend is also observed in the eastern part of the Czech Republic during the July–September (JAS) period. The drying during the JAS period was largely driven by changes in August. A detailed assessment of the soil moisture trends can be found in Trnka *et al.* (2014a).

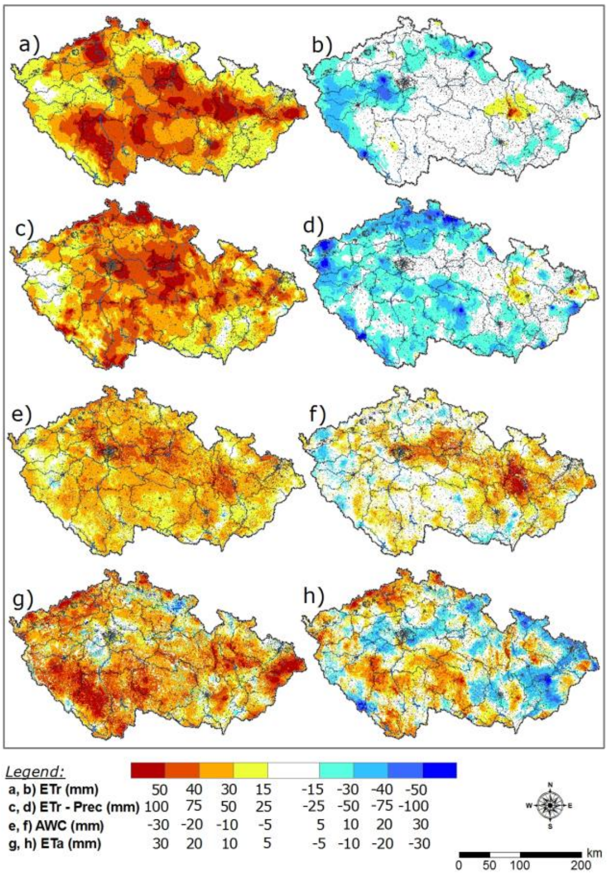

Figure 1. Statistically significant trends in key parameters of the water balance: (a) reference evapotranspiration (ET_r) for the April-June period (AMJ); (b) ET_r for the July-September period (JAS); (c) difference between precipitation and ETr for the AMJ period; (d) same as (c) but for the JAS period; (e) soil water content in the 0-1.3 m soil profile during AMJ; (f) same as (e) but for JAS; (g) actual evapotranspiration (ET_a) during AMJ; (h) same as (g) but for JAS. All trends were calculated for the 1961-2012 period. Trends conducive to drought are depicted by a yellow-red color scheme, and tendencies toward wetter conditions are shown in a blue-green color scheme. The trend significance was determined for every grid according to Spearman's rank correlation coefficient ($p = 0.05$).

Fig. 1 also presents the prevailing trends in the reference evapotranspiration over the 1961–2012 period from April to September. The ET_r has increased over the entire period, particularly in the months of April, May, and August, whereas there was virtually no tendency toward lower ET_r during the March–September period. Figs. 1a–b demonstrate a significant increase of ET_r during the AMJ period (by more than 50 mm at many sites) as well as a tendency of decreasing ET_r in the JAS period in the western part of the country. In terms of precipitation, the AMJ period showed a certain tendency toward decreasing precipitation in the northwest part of the territory. For the month of July, most of the western half of the Czech Republic displays a tendency toward higher precipitation. When we examined the differences between reference evapotranspiration and precipitation (Fig. 1c–d), which represent two key components of the landscape water balance, the balance tended to become negative (indicating an increasing difference between the potential needs of the vegetation and the available precipitation) between April and June in the majority of grids, whereas the trends in these values were less pronounced in the JAS period. The overall trends for the AMJ period (Fig. 1c) indicate an increase in the difference between ET_r and precipitation greater than 100 mm during the 1961–2012 period.

Because of the importance of trends in ET_r in any water-balance assessment, we compared the ET_r trends and the observed pan evaporation data. The pan evaporation between 1968 and 2010 from five representative stations show good agreement between modeled ET_r and the pan evaporation data, although the ET_r values are significantly higher than the pan evaporation estimates. Overall, rather good agreement was noted between the observed pan evaporation and ET_r trends. The agreement of the trends in the modeled (ET_r) and measured (pan evaporation) variables is strongest at the Doksany, Kostelní Myslová, and Cheb stations, which have relatively stronger drying trends.

There is a clear tendency toward higher global radiation values, with more than half of the grids displaying positive trends in April, May, and August, whereas less than 1 % of the grids display the opposite tendency from March to September. At least 73 % of the grids display sustained significant trends toward higher temperatures from April to August with virtually no cooling trends. A decrease of the relative humidity in more than 80 % of the grids was observed in April and May, with other months displaying a less pronounced decrease; however, even in the case of relative humidity, almost no regions exist in which an increase in relative humidity would be reported. A widespread trend toward lower wind speed, which is conducive to decreasing ET_r, is the only factor that partially contradicts the trends in global radiation, temperature, and relative humidity.

Water from melting snow is critical for the recharge of the soil moisture at the beginning of the growing season. The decline in the total amount of precipitation in the form of snow is pronounced in the eastern region of the Czech Republic and at higher elevations. This change is significant for a large number of grids, particularly in the western half of the territory.

Changes in the onset of phenophases significantly affect the soil moisture levels via changes in the leaf area index (which affects actual evapotranspiration) and through root growth, which allows for water uptake from deeper layers as the growth season progresses (particularly on arable land). On average, the peak of the growing season begins 12 days earlier. This suggests that in lowland production areas, certain surfaces achieve the maximum area of evapotranspiration as early as late May, which is notably sooner than in the 1960s and 1970s, when the same peak was reached in the second week of June. It leads to an increased water demand earlier in the season and a decrease in the soil moisture if there is no corresponding increase in precipitation totals to replenish the water reserves.

When analyzing the trends of actual evapotranspiration (ET_a) for the entire AMJ and JAS periods (Fig. 1 g–h), we can clearly identify the prevailing trends in the AMJ period and the regionally diverse trends in the JAS period. The trends in actual evapotranspiration are affected first by the trends in the ET_r (i.e., driven by the evaporative demand of the atmosphere), but they also depend on the available soil moisture (i.e., controlled by the available water). It means that the ET_a can increase only if there is evaporative demand, if the soil moisture is sufficient to support such an increase, and if there is vegetation cover capable of withdrawing the water from the soil. Therefore, we observed significant areas of the country with increased ET_a particularly in March and April, which in turn leads to a progressive decrease in the soil water content. When the decrease in soil moisture began to affect the water availability in certain grids, this development had consequences for the ET_a in May and June. Thus, the trends from July to September are highly dependent on precipitation but are still sensitive to ET_r trends as well. In summary, as the soil water reserves become gradually depleted, the ET_a values become more dependent on rainfall, and no significant trend (or even a decrease in ET_a) can be observed. The character of the ET_a trend depends largely on the ratio between the ET_r and precipitation. In regions with relatively ample rain, the ET_a has increased significantly (at higher elevations) over a longer period of the growing season compared with the regions in which precipitation is lower (thus limiting the available soil moisture and therefore the ET_a). The relationships between the key drivers of May–June drying are qualitatively assessed in Fig. 6. This figure summarizes the causes of the observed drying over the territory, which are not.

CONCLUSION

A decrease in soil moisture in May and June in the Czech Republic should be of great concern because these months influence the key portion of the growing season for this region. Moreover, the fact that the AMJ period of 2001–2012 displayed a 50 % increase in drought probability compared with 1961–1980 is alarming. The probability of extreme drought was also found to be increasing significantly. The reported trend patterns are of particular importance with respect to the expected climate change, given the robustness and consistency of the trends shown and the fact that they can be aligned with the existing climate model projections.

Acknowledgement

The projects “Establishment of International Scientific Team Focused on Drought Research” (No. OP VK CZ.1.07/2.3.00/20.0248) and KONTAKT LD 13030 financed the analyses. PH was supported by the project “CzechAdapt NF project”. RB, MT and PD were supported by GACR projects(P209/11/0956 and 13-04291S/P209, respectively), and PS, MM and ZZ were supported by the project of the National Agency for Agricultural Research (Nos. QJ1310123). This work was supported by the Ministry of Education, Youth and Sports of CR within the National Sustainability Program I (NPU I), grant number LO1415.

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