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Abstract

The awareness of drought and its impacts on Central Europe increased after the significant drought episodes in 2000, 2003, 2012 and 2015, which were all estimated to have caused over 500 million Euro in damage in the Czech Republic alone. These events indicated the need for timely and high-resolution monitoring tools that would enable analysing, monitoring and forecasting of drought events. Monitoring soil water availability in near real time and at high-resolution (up to 0.5×0.5 km for some products) helps farmers and water managers to mitigate impacts of these extreme events. The Czech Drought Monitor was developed between 2012 and 2014 and has since been operational as an online platform. It uses an operational modelling system that consists of four pillars: (a) weekly soil moisture estimates based on spaceborne Advanced Scatterometer sensor measurements; (b) the daily SoilClim soil moisture model, which runs based on high-density network data from the Czech Hydrometeorological Institute with a 55-year reference period; (c) weekly reports on vegetation condition, which is deduced from satellite-based vegetation indices and early warnings of imminent drought impacts; and (d) weekly reports of soil moisture, especially after drought impacts, which are provided by dozens of experts. Since 2016 the drought forecast (+9 days) has been released daily based on an ensemble of five numerical weather prediction models combined with a weekly drought outlook (+2 months). The analysis of four recent episodes (2000, 2003, 2012 and 2015) clearly showed that both large-scale and regionally restrained drought episodes posed serious risks in terms of their impacts and damage. Comparisons with historical droughts showed that these events, especially the 2000, 2003 and 2015 events, were among the top five drought episodes in the June–

August period observed in the Czech Republic since 1961 in terms of spatial extent, magnitude and duration.

KEYWORDS

drought impact reporters, extreme events, microwave radar, remote sensing, soil moisture modelling, SoilClim

1 | INTRODUCTION

Drought is a natural phenomenon that results mainly from deficiencies in precipitation compared to the expected or normal amount (Wilhite, 2005). Droughts have the largest spatial extent and the longest duration of all natural disasters (Sheffield and Wood, 2011); they tend to develop slowly and persist over several years. The drought events can reach regional (e.g. Hunt *et al*., 2014; Zahradníček *et al*., 2015) national (e.g. Zink *et al*., 2016) and continental scales (Svoboda *et al*., 2002; Samaniego *et al*., 2013). Recently phenomena of flash drought events, that is, sharp intensification of lower intensity droughts occurring in the space of days or weeks have been studied and described (Hunt *et al*., 2014; Otkin *et al*., 2018). As described by Brázdil *et al*. (2016), even in Czech Republic droughts may have serious socio-economic consequences, including socio-political unrest but in other parts of the World famine, epidemics and human migration are unfortunately common (e.g. Heim, 2002; Mishra and Singh, 2010). The recent drought episodes in Russia in 2010 (Trenberth and Fasullo, 2012), the United States in 2011–2012 (Hoerling *et al*., 2013), China in 2013 and Brazil in 2014 were (for each particular year) among the 10 worst natural disasters worldwide in terms of the highest recorded damage (Munich *et al*., 2014). A series of recent droughts sparked widespread research activity, which led to the deployment of high-resolution drought monitoring schemes in the Czech Republic (after the 2012 drought), Germany, Austria and Slovakia (after the 2015 drought). This is understandable, as the economic damage caused to Czech economy (especially to agriculture sector) by droughts is comparable to that of floods which represent the two most disastrous natural events that affect this region (Trnka, Personal communication). Therefore based on scientific recommendations specific agricultural drought warning and forecasting system has been introduced in similar manner as in the case of floods, which is provided by the Czech Hydrometeorological Institute (CHMI, http://hydro.chmi.cz/hpps/main_rain.php?lng=ENG).

Droughts have impacts on many societal sectors, including agriculture, forestry, water resource management, energy generation, health of ecosystems and people. Their impacts can be divided into direct and indirect impacts (Wilhite *et al*., 2007), with direct impacts including (among others) reduced crop yield and forest productivity, increased forest fire hazards, reduced water levels, and increased mortality rates for livestock, wildlife and fish. These direct effects are usually followed by societal response (e.g. Brázdil *et al*., 2016) aimed at improving drought resilience in a particular region. Such events often lead to response in terms of legislation (e.g. after the 1947 drought in Central Europe; Brázdil *et al*., 2016) or the introduction of drought monitoring systems, such as the establishment of the U.S. Drought Monitor after major drought events in the late 1990s (Svoboda *et al*., 2002). One indirect drought impact is food price volatility, which is potentially exacerbated by market effects in the agricultural sector. As a result, it is difficult to estimate total costs and losses at regional and national levels. Indirect losses of droughts often exceed direct losses (Wilhite *et al*., 2007), but they are more difficult to link with a particular event, especially in more affluent countries, where direct impacts seem to attract the most attention.

In this study, we (a) review the existing drought monitoring systems capable of covering agricultural drought; (b) describe the approach used to monitor agricultural and forest droughts and to promote drought awareness; (c) demonstrate that the Czech Drought Monitor (CzechDM) can be used effectively monitor events using the events of 2000, 2012 and 2015 as examples; and (d) test the ability of the system to forecast droughts.

1.1 | Existing drought monitoring systems

Drought monitoring systems are already available over large parts of the world. They serve different purposes depending on the geographic situation and size of the regions covered. On a national scale, the pioneering system (i.e., the U.S. Drought Monitor) has been operational since 1995 (Svoboda *et al*., 2002). It has inspired many follow-up activities around the World. On a continental scale, a spin-off of the U.S. Drought Monitor was the North American Drought Monitor, which was introduced in early 2000 (Lawrimore *et al*., 2002). This was followed by the development of the European Drought Observatory (http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1042) and a drought monitoring/forecasting system in Africa (Sheffield *et al*., 2014). Worldwide drought monitoring systems include systems proposed by Pozzi *et al*. (2013), Hao *et al*. (2014) or Standardized Evapotranpiration Precipitation index (SPEI)-based Global Drought Monitor (e.g. Vicente-Serrano *et al*., 2012).

The time resolutions of these systems range from multiple days to 1 month, and the spatial resolutions span from square kilometres to hundreds of square kilometres. In general, the frequency and resolution of national systems are higher than those operated at continental or global scales. Nevertheless, some exceptions exist. For instance, the European Drought Observatory provides outputs on a 1 × 1-km grid, which is a higher resolution than that of many national monitoring systems in Europe (e.g. Zink *et al*., 2016). The tools used by various systems clearly differ, ranging from fairly simple approaches based on drought indices (Vicente-Serrano *et al*., 2010) to multi-indicator systems (Svoboda *et al*., 2002) and process-based hydrological models at high resolutions (Zink *et al*., 2016). Two principle approaches that determine the presence of droughts over a given territory are generally used: the first approach relies on a set of preselected indicators (e.g. the Global Drought Monitor using the SPEI) or process-based models (e.g. the German Drought Monitor using soil moisture), and the second uses the convergence of evidence approach, which is usually carried out by the work of expert(s) who analyse not only weather- and satellite-based tools but also consider observed impacts (e.g. the U.S. Drought Monitor). In the latter approach, drought evidence could be presented in the form of a single map (U.S. Drought Monitor) and/or summed-up in text form with selected key indicators made available to the user.

1.2 | Rationale behind the CzechDM

Global/continental drought systems primarily serve to provide drought maps at a large scale; however, it is relatively difficult to use these systems for operational management at the local level. The monitoring of droughts over national territories must respond to different stakeholders and serve different purposes than that at global/continental scale systems. National systems are usually designed to aid in decision-making at the strategic level (e.g. declaring emergencies), where greater detail and local knowledge allow them to be used for operational decisions by various stakeholders (e.g. farmers, water companies and foresters). Given the large spatial variability of soil conditions and the desire to use the system to aid in decision-making at the farm level, a fairly high spatial resolution of 500 m is chosen for the CzechDM. The system relies on several data sources. The key data set is based on the daily observations from the CHMI, which provides the densest and most reliable meteorological data available for the Czech Republic. Complete time series of ground observations (described in 3.1) extend back to 1961, which allows for the construction of a 50-year reference period (1961 to 2010). Similar to the U.S. Drought Monitor, the remotely sensed data and text summaries are updated weekly while soil moisture models and in particular forecasts are updated in daily time step. As reported by Zink *et al*. (2016), the implementation of a national drought monitor encourages local experts, stakeholders and decision-makers to take part in the future development of improved drought monitoring strategies. The CzechDM took this collaborative approach a step further and is currently using products that are based on information provided by network of dedicated drought reporters.

2 | CzechDM OPERATIONAL SET-UP

The CzechDM emphasizes agricultural-/forest-related drought conditions and is based on four pillars (Figure 1). Pillar I provides information on soil moisture based on microwave radar measurements at the Central European level; Pilar II: soil moisture model at a 500-m spatial resolution which uses near real-time observed meteorological data from a dense network of stations augmented with ground soil moisture measurements; Pilar III: drought reports provided by farmers/foresters and Pilar IV: remotely sensed vegetation conditions that provide near real-time information not only on the soil moisture status but also on drought impacts. The soil moisture and vegetation condition data are compared to their corresponding values over the reference period. The reference periods differ based on the product: for modelled soil moisture data (Pillar II), the 1961–2010 reference period is used; for Pillar I, Advanced Scatterometer (ASCAT) data from 2007 to present serve as reference; for Pillar III the impacts observed during the last 5 years serve as reference while for condition of vegetation data (Pillar IV), the period 2000 to present is considered. The CzechDM is versatile enough to be used not only for monitoring but also for the evaluation of past droughts

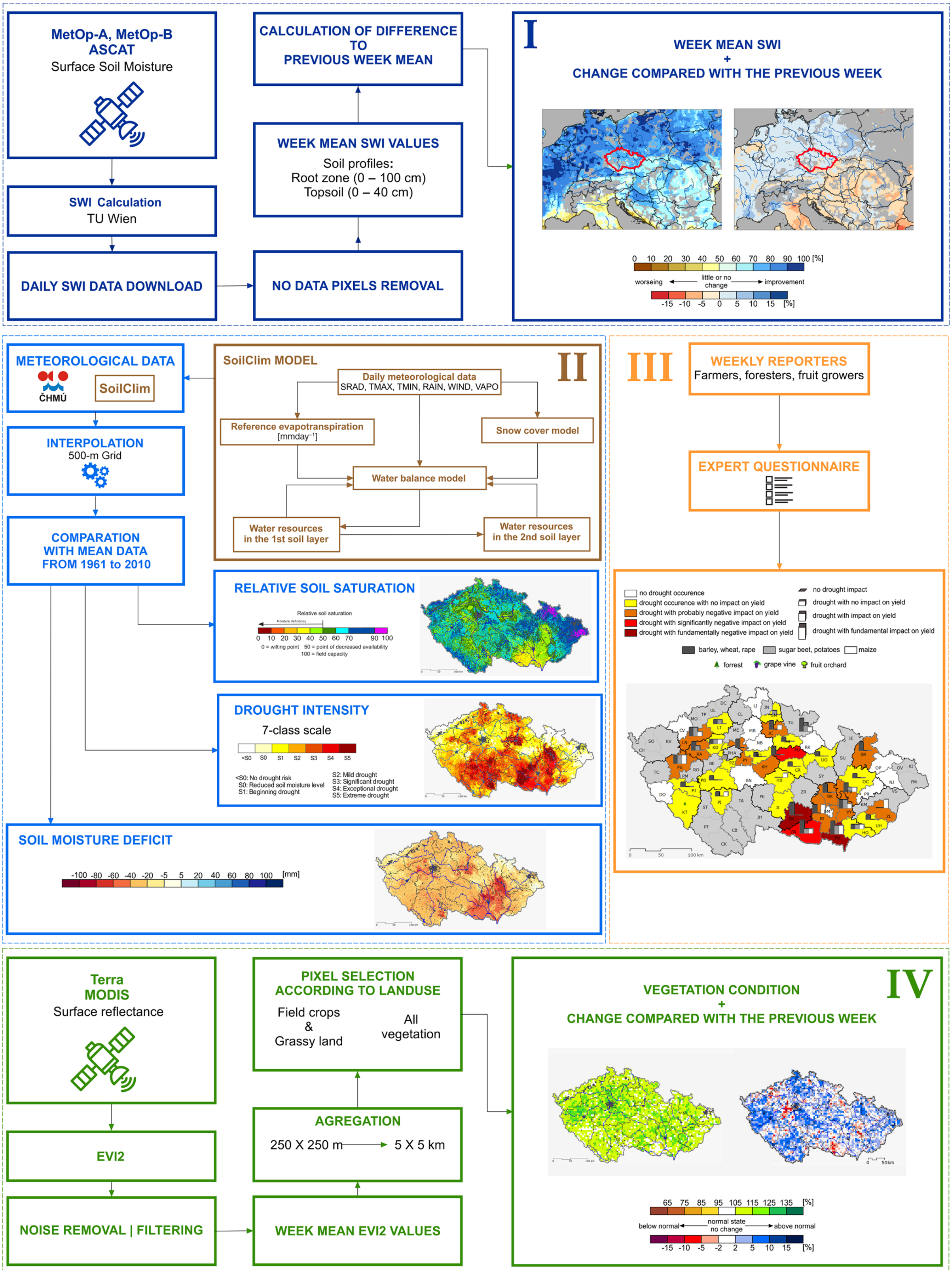


FIGURE 1 Legend on next page.

and drying trends (Trnka *et al.*, 2015a; 2015b), the ranking of historical drought events and drought prediction (the last two are evaluated in this article). An overview of the operational system and its four pillars are presented in Figure 1.

2.1 | Soil moisture monitoring

The core of the CzechDM is based on the Pillar II and relies on daily weather data that are collected by the CHMI in the station network. These data are initially quality checked by the CHMI and sent to the CzechDM server located in the CHMI Agrometeorological Observatory in Doksany. Then, the CzechDM software runs additional quality control checks and detects outliers. Potentially up to 400 precipitation stations and almost 200 climate stations that collect minimum and maximum air temperature, mean relative air humidity, global radiation or sunshine duration, and wind speed data are used to derive the daily meteorological input data for the soil climate model, SoilClim (Hlavinka *et al.*, 2011).

The daily data are interpolated by a regression via kriging, which uses geographical coordinates, elevation and other terrain characteristics as predictors. In the Czech Republic, the average minimal distance between two neighbouring stations is approximately 22 km for elements measured at climatological stations and less than 10 km for those measured at precipitation stations. The daily incident solar radiation accounts for slope, aspect and horizon obstruction using the methodology proposed and tested by Schaumberger (2005). The soil moisture content is estimated using the SoilClim model (Hlavinka *et al.*, 2011), which is principally based on the modelling approach suggested by Allen *et al.* (1998). SoilClim is applied to each grid and accounts not only for the soil water holding capacity within the grid but also for the type of vegetation cover, phenological development, root growth and snow cover accumulation, sublimation, and melting (Trnka *et al.*, 2010). The module for actual evapotranspiration (ET_a) and soil water content estimates considers two soil layers: the topsoil layer (from the ground surface to a 0.4 m depth) and the subsoil layer (between 0.4 and 1.0 m). The cascading approach for water movement from the topsoil to the subsoil layer is used when the topsoil is more than 50% saturated. In the case of higher soil water content in the topsoil, the soil water is allowed to seep into the subsoil, which mimics macropore and preferential water transports (Hlavinka *et al.*, 2011).

SoilClim estimates of the soil moisture content are affected by the maximum soil water holding capacity (MSWC) for both of the soil layers in each grid cell. This parameter is estimated through a combination of digital maps and detailed soil physical data from 1,073 soil pits, which are collected by the Czech National Soil Survey (more details in Trnka *et al.*, 2015a; 2015b). The MSWC is calculated by assuming a 1.0-m soil profile. If the soil database indicates a shallower soil depth it is used instead. The properties of the topsoil (0–0.4 m) and subsoil (0.41–1.0 m, or the maximum rooting depth when the soil is shallower) layers are defined separately based on the available soil data. In addition, grids in which at least some part of the growing season is influenced by high underground water tables (which are likely to be reached by roots during natural subsurface irrigation) and that therefore respond to drought differently (both in terms of stress magnitude and timing) are compared against the other grid cells. Soils with an observed gleyic process with close proximity to (and at the same altitude as) water bodies, peat, and bog areas had significantly slower soil moisture depletion rates than neighbouring grids without such an influence (Trnka *et al.*, 2015a).

The SoilClim model has been shown to explain between 74 and 80% of the daily of ET_a variability measured by eddy covariance and Bowen ratio systems over three sites and six crops, with root mean square error (RMSE) ranging from 0.49 and 0.99 mm/day (Trnka *et al.*, 2015a; 2015b). SoilClim also performed well at the lysimetric station Hirschstetten in Austria (in the period 1999–2004) for three soils, explaining up to 63% (topsoil) and 74% (subsoil) of observed soil moisture with RMSE ranging from 2.82 to 4.23% for both layers. At field conditions we have found SoilClim to explain 63% of topsoil and 74% subsoil soil moisture variability (Trnka *et al.*, 2015a). SoilClim reproduces fairly well changes in the long-term soil moisture dynamics in the topsoil especially during April to September periods, that is, window critical for agriculture drought development. SoilClim also reproduced well trends in the reference evapotranspiration proxy, that is, pan evaporation between 1968 and 2010 from five representative stations across Czech Republic (Trnka *et al.*, 2015b). Although the ET_r values estimated by SoilClim were significantly

FIGURE 1 Scheme of the CzechDM weekly procedure showing the four main pillars: I, providing a wider context for the current soil moisture situation from a central European perspective; II, based on soil moisture modelling using a dense weather station network; III, using several hundred drought reporters; IV, Quantifying the impacts of drought on vegetation conditions higher than the pan evaporation estimates it nevertheless explained significant portion of monthly ET_r variability (more than 60% at each site). In an update of Trnka *et al*. (2015a) the SoilClim was shown to explain over 62% of daily topsoil soil moisture variability for April–September during 1961–2018 in Doksany station. This is an improvement over 55% reported for 1961–2012 period by Trnka *et al*. (2015a) arising from using improved soil parametrization of SoilClim and improved methods of crop cover dynamics introduced since 2015.

SoilClim dynamically simulates the vegetation cover and considers changes of its parameters in daily time-step (e.g. changing rooting depth or crop height in case of crops or presence/absence of leaf in case of deciduous forests). The changes are driven by the thermal time and vernalization requirements (depending on the crop cover type). Therefore, crop parameter K_c (Allen *et al*., 1998) and the root growth dynamics vary for individual vegetation covers throughout the year (or the vegetation season). To simplify the seasonal variations in crop cover compositions on arable land grids (which dominate the landscape), a fixed proportion of crops on each arable grid is assumed. In these grids, the soil moisture content is computed using spring and winter (C_3) crops (based on the current spring barley and winter wheat yields) and spring (C_4) crops (maize); then, the three considered crops are weight-averaged.

Information regarding the land cover relies on the Corine land cover 2006 data set – Version 16 (April 2012). Overall, the monitoring system uses the following land use categories: (a) arable land (46.2% of the area), (b) permanent grasslands (7.6%), (c) conifer forests (20.3%), (d) deciduous forests (3.1%), (e) mixed forests (6.0%), (f) other agricultural areas (8.7%) and (g) grids where calculations are not performed [i.e., urbanized areas (7.0%) and water bodies (1.1%)].

Given the quality of the soil data that are available at a 5 m resolution, a 100 m resolution utilized to analyse the land cover data, density of weather stations, complexity of terrain and requirements from farmers considers the cadaster (i.e., local) unit resolution to be necessary; therefore, the 500 m grid was adopted. Station weather data as described in 3.1 are utilized with an approximate 1-day time lag, and the complete product is available within 30 hr after the input data collection.

In the second pillar, the absolute soil moisture content is compared with the archived 1961–2010 data, which are referred to as the reference period. The resulting soil moisture content is compared with the soil moisture on a given day (and within an interval of ±10 days) during all years of the reference period. During this process, the soil moisture content anomaly is transformed into a percentile, which is then translated into a drought class and visualized. The visualization of the drought events is carried out in close collaboration with the U.S. Drought Monitor team using six classes. Table 1 shows five classes are defined by drought conditions, and the sixth class describes the abnormally dry prewarning state (Svoboda *et al*., 2002).

TABLE 1 The classification of droughts via the CzechDM based on the AWR percentile

Drought level	Description of the drought level
S0	Reduced soil moisture with a return probability between 3 and 5 years – usually precedes and follows a major drought
S1	Minor drought – return probability between 5 and 10 years
S2	Moderate drought – return probability between 10 and 20 years
S3	Severe drought – return probability between 20 and 50 years
S4	Exceptional drought – return probability between 50 and 100 years
S5	Extreme drought – return probability of 50–100 years and a soil water content below 50% of the maximum water holding capacity for at least 1 month

The five drought classes range from moderate (where vegetation is prone to water stress) to extreme (i.e., a high probability of crop loss and increased forest fire risk). These classes are derived using the return periods in Table 1. These thresholds reflect the occurrence of similar conditions in the past and, thus, indicate the potential impacts of these conditions. Because the soil moisture anomaly describes the status of the soil but not necessarily the impacts on vegetation, other pillars are used to help establish a link between the observed soil moisture levels and drought impacts.

2.2 | Remote sensing component

The greatest advantage of using remote sensing data to monitor drought conditions is the ability to obtain information regardless of national borders and with much higher spatial detail than that of ground-based data. In addition, remote sensing satellites provide data that are independent and complementary to those based on ground observations. Pillars I and IV are based on these data and, while the benefits of using remote sensing data are somewhat offset by the required post-processing and the resultant lag time in the data availability, they are an important part of the CzechDM.

2.2.1 | ASCAT data-based soil moisture estimates

The Soil Water Index (SWI) used by the CzechDM, which is operationally produced and disseminated by the Copernicus Global Land Service (https://land.copernicus.eu/global/). It is primarily used to validate the SoilClim-based estimates of Pillar II (Figure 1). The SWI quantifies the soil moisture conditions (percentage) in the soil profile (Wagner *et al*., 1999), where the CzechDM uses the data to specify the wetness conditions in the 0–100- and 0–40-cm layers. The SWI is calculated via remotely sensed surface soil moisture (SSM) observations using a simple two-layer water balance model (Ceballos *et al*., 2005). Before calculating the SWI, ASCAT measurements affected by snow or frozen surface conditions must be discarded.

The SSM product is derived from backscatter observations collected by the ASCAT aboard a series of MetOp satellites. Scatterometers are side-looking real-aperture radars that transmit short microwave pulses down to Earth's surface and measure the power of the echoes returned to the instrument. The measured backscattering coefficient is dependent on the dielectric properties of the soil surface, the roughness of the soil surface, and the scattering and absorption properties of the overlying vegetation. Therefore, to retrieve the SSM from the ASCAT, backscatter observation retrieval approaches that disentangle the contributions from all of these surface variables are needed. For retrieving the ASCAT SSM data, a physically motivated change detection method is used (Wagner *et al*., 2013). Within the CzechDM, SWI data are displayed in regular latitude/longitude grids with a WGS 1984 ellipsoid (terrestrial radius of 6,378 km) at a 0.1° resolution. The reference is the centre of the pixel, which means that the longitude of the upper left corner of the pixel is equal to the pixel longitude minus half of the angular resolution. Every Monday, the data for the past 7 days (i.e., from last Monday to Sunday) are downloaded from http://land.copernicus.vgt.vito.be/PDF/datapool/Water/Soil_Water/.

Each day, information on soil moisture for the 0–100- and 0–40-cm soil layers are extracted separately, and pixels displaying frozen soil (based on a surface state flag provided with the SWI) are deleted. Consequently, two maps (a separate map for the root zone layer and one for the shallower layer) are created to represent the weekly mean. These maps are presented to users with supplementary probability maps to show the difference in SWI between the current and previous weeks.

2.2.2 | Vegetation condition

Vegetation indices based on surface reflectance measurements are often used for monitoring the phenological status (e.g. Reed *et al*., 1994), vegetation stress occurrences including drought (e.g. Brown *et al*., 2008), agricultural yield estimations and forecasting (e.g. Moriondo *et al*., 2007; Mkhabela *et al*., 2011). This approach assumes that meteorological conditions within a certain season are reflected in the state of the vegetation. This way, both positive and negative effects should be mirrored in the vegetation. For this reason, remote sensing assessments based on reflectance analyses are selected as Pilar IV of the CzechDM, even though not only drought stress but also other factors (e.g. an earlier or later start or end to the season, land use change, and impacts of pest and disease infestation) affect vegetation. Namely, the relative vegetation condition is assessed within the CzechDM at a weekly time step throughout the course of the vegetation season. The spatial product resolution is 5 km and is based on the Two-band Enhanced Vegetation Index (EVI2), which is derived from reflected near-infrared and visible red radiations (Jiang *et al*., 2008; Rocha and Shaver, 2009). These two bands are based on observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite (operated by National Aeronautics and Space Administration [NASA]) at a daily time step. In this study, the Version 5 MODIS/Terra MOD13Q1 data used are obtained through an online database at the NASA Land Processes Distributed Active Archive Center, which is located at the USGS Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota (https://lpdaac.usgs.gov/get_data). Both bands are downloaded at a 250-m resolution and recalculated into the EVI2.

Consequently, a smoothing procedure (due to various atmospheric conditions and cloudiness) is used separately for the data rows within each grid (250 × 250 m). The smoothing procedure consists of several steps. First, unlikely sudden decreases by more than 2 standard deviations in the daily time series are identified as probable errors and removed. For this purpose, daily values observed within a window for the last 10 days are analysed, and missing or removed data are linearly interpolated. Due to the variation in the EVI2 time series, which is caused by the utilization of crop rotation schemes and changing crop patterns between seasons, the values are aggregated into a grid with cells that are 5 × 5 km in size at a weekly time step (i.e., the average value of all pixels inside a cell represents the cell value). For each cell, the prevailing type of land cover is determined using the Corine land cover 2006 data set – Version 16 (April 2012). Then, the reclassification of the dataset for all vegetation categories into seven main categories is carried out, with the exclusion of artificial surfaces, water bodies and wetlands: (a) arable land, (b) heterogeneous agricultural areas, (c) grasslands and pastures, (d) broad-leaved forests, (e) coniferous forests, (f) mixed forests, (g) scrublands, herbaceous vegetation associations and/or bare areas.

The situational assessment (including the possible drought impacts) based on the EVI2 deviation for a given week (and on the same 5 × 5-km grid) from 2000 to 2016 in the reference period form the fourth pillar of the CzechDM. Such differences in the percentage of the average value are referred to as the relative vegetation condition. To depict drought impacts within various vegetation categories, two variants of this product are derived each week. The first one is the relative condition over agricultural areas (e.g. field crops in arable lands, grasslands and pastures), and the second variant includes information from pixels composed of all vegetation categories (including forests). Finally, to detect the overall tendency in the vegetation status, the change in status from that of the previous week is also used.

2.3 | Observed impacts

The map with drought impacts represents the Pilar III of the CzechDM (Figure 1) which can be accessed at www.intersucho.cz/en/. This product is based on cooperation with respondents or reporters (mainly agricultural farmers) but also fewer numbers of winegrowers and foresters, who share their actual evaluations of drought impacts on given crops and the state of soil moisture in weekly time steps. Sharing this information is possible via a website tool with a publicly accessible questionnaire at the following link: http://www.intersucho.cz/cz/dotaznik/. The questionnaire contains 10–14 simple questions according to the reporter's field of interest (i.e., agronomy, fruit orchards and viticulture, and forestry) and is available in multiple languages (https://questionnaire.intersucho.cz/en/).

The first three questions are the same for all three questionnaires and are based on an evaluation of soil moisture in the topsoil layer (i.e., the actual soil moisture, the soil moisture during the last 3 months and the change from the previous week). The evaluation of soil moisture in the topsoil is based on a simple fingerprint assessment, where the scale moves away from dry and dusty soils without the possibility of fully saturated soil sticking to fingers (e.g. https://www.cdpr.ca.gov/docs/county/training/inspprcd/handouts/soil_moist_feel_test.pdf). The scale for the water balance during the last 3 months can be assigned to seven different classes, which include very dry, normal and very moist conditions. The fourth question contains feedback from reporters regarding the accuracy of the current soil moisture estimations at the farm level using high-resolution maps from the Local Administration Unit 1 (LAU1), which are generated each week. The map content is rated on a scale from 1 (i.e., the map reflects the situation precisely) to 5 (i.e., the map is useless). The remaining questions focus on the specific impacts observed by key crops, fruit trees or forest types. Each reporter provides information regarding the drought situation on his/her plots and the expected decline in yield or observed decline in yield after the harvest. The decline in yield is defined as a percentage decrease compared to the average yield during the past 3 years.

The rating system performed well during the 2017 and 2018 drought episodes. When the drought quantification methods presented in Section 3.2 together with the drought impact reports were used as predictors of yield declines at the level of individual cadasters then over 95% of all cadasters with yield declines of 30 and 50% below 3-year average have been successfully identified with drought reporters showing a high (over 90%) level of accuracy.

During 2017 close to 300 respondents are actively participating in providing information on the drought status and drought impacts at their farms and forests, with approximately 120 of these respondents reporting each week (with a maximum of 143 during the peak of the 2017 drought). This cooperation with reporters started during the vegetation period in 2014, particularly due to cooperation with the Agricultural Chamber of the Czech Republic, which has increased the number of reporters from 53 LAU1 districts (from a total of 79). The drought of 2018 has brought number of reporting LAU1 units to 64 with over 230 weekly reporters providing separate reports for over 650 cadaster units every week. As drought continued well into 2019 the number of reporters reached 400 reporters per week during April–August of 2019. During 2019, the number of cadaster units with reported data was constantly over 1,000. Maintaining this high level of response is not solely a function of drought intensity but developing long-term relationship with the reporters and constant two-way communication and promoting of the service. However a decrease of number of the drought reporters in wet years is to be expected.

2.4 | Drought forecasting and drought outlook

The efficient management of water resources during drought events requires not only drought status information but also a drought forecast. Within the CzechDM, an ensemble of five numerical weather prediction (NWP) models up to 9 days in advance is used: the Integrated Forecasting System [IFS, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF)], Global Forecast System (GFS, provided by National Oceanic and Atmospheric Administration Nationals Venters for Environmental Prediction), Global Environment Multiscale [GEM, provided by the Canadian Meteorological Centre (CMC)], Unified Model provided by the UK Met Office (Global UM) and Action de recherche petite echelle grande echelle [ARPEGE, provided by the National Center for Meteorological Research (CNRM)]. The models were selected based on their performance for the Czech territory, lead time of the forecast and also availability. The resolutions of the NWP models vary from 0.25° (GFS), 0.24° (GEM) and 0.234° in longitude to 0.156° (approximately 17 km, Global UM) and 0.1° (IFS, ARPEGE) in latitude. The NWP models use various physical parametrizations and different data assimilations; therefore, they differ when forecasting individual meteorological elements, as they are stronger or weaker under particular circumstances. The best results are achieved when we combine different NWP models, each of which are given a weight according to the constantly running comparisons with the observed data. The IFS, GFS and CMC models provide a 9-day forecast; the guide to the expression of uncertainty in measurement is available in our ensemble for 6-day forecasts and in ARPEGE for 4-day forecasts.

The NWP models are downloaded daily from the file transfer protocol (FTP) servers and are downscaled and further processed via the methods described by Štěpánek *et al*. (2018). This involves the correction for model biases by comparing the model outputs with the station data via quantile mapping (Štěpánek *et al*., 2016). Daily forecasts of all SoilClim model weather inputs are prepared, and the values in the network of grid points pertinent to each individual NWP model are then interpolated into the same raster as the station data (500-m resolution). Thus, grids with measured station data and modelled data are matched and modelled data bias corrected and then used as SoilClim inputs. The procedure is applied for each required meteorological element (i.e., air temperature, precipitation, relative humidity, wind speed, and solar radiation), which serve as the inputs for SoilClim. The running evaluation of the NWP model outputs is carried out weekly for the previous week/3-week periods, and the validated statistics are presented on the web page for drought monitoring; therefore, users are aware of the near real-time individual model performance (the model performance is shown later in Section 6). The hindcasting based analyses are done off-the line and are being analysed in a separated study (Stepanek, Personal communication). The CzechDM approach utilizes ensemble of five NWP models each of which is utilized in its deterministic mode. The deterministic forecasts by individual NWPs (as opposite to ensemble mode) offer significantly higher resolution compared to ensemble forecasts, which is important given relatively small area of the Czech Republic. Global models (as opposed to limited area models) are CzechDM choice due to the longer forecasted period (e.g. Štěpánek *et al*., 2016).

Apart from the NWP models, the CzechDM uses statistical forecasting for up to 2 months, which shows the probability of soil moisture reaching normal or above normal values in the next 1, 2, 4 and 8 weeks. While the actual weather data used are up to date when the forecast is issued, the 1961–2016 weather data (where each year has an individual realization) are used for the outlook period. The outlook evaluates the likelihood of improving drought situations considering the weather patterns in the previous half century. We tested performance of the statistical forecasting during 2017 and 2018 period using Brier's Quadratic Probability Score [or simply Brier score (BS)], a probability analogue of mean squared error. This measure-oriented approach compares the forecast probability with the realization of a binary event that is represented by a given variable taking value 1 or 0 depending upon the occurrence of the event. The BS ranges from 0 to 1 with a score of 0 corresponding to perfect accuracy, and is a function only of the difference between the assessed probabilities and realizations (Brier, 1950).

3 | RECENT DROUGHT EPISODES

The Czech Republic has experienced several drought events since the end of the 20th century and two major events during the implementation of the CzechDM. We selected three events in 2000, 2012 and 2015 (Figures 2 and 4) to assess the performance of the CzechDM and to showcase a variety of drought situations that the CzechDM is designed to monitor.

The first event began to evolve in the spring of 2000, which lead to significant soil moisture anomalies in May and June (Figures 2 and 3), and a return to normal values occurred in July. However, both summer and winter crops had already been damaged, and July precipitation was unable to save the harvest, which was also documented by poor vegetation conditions before the harvest (Figure 4). The crop yields were exceptionally low, as shown in Brázdil *et al*. (2009) and Hlavinka et al. (2009), particularly for crops sown in spring and those with a short vegetation season (e.g. spring barley).

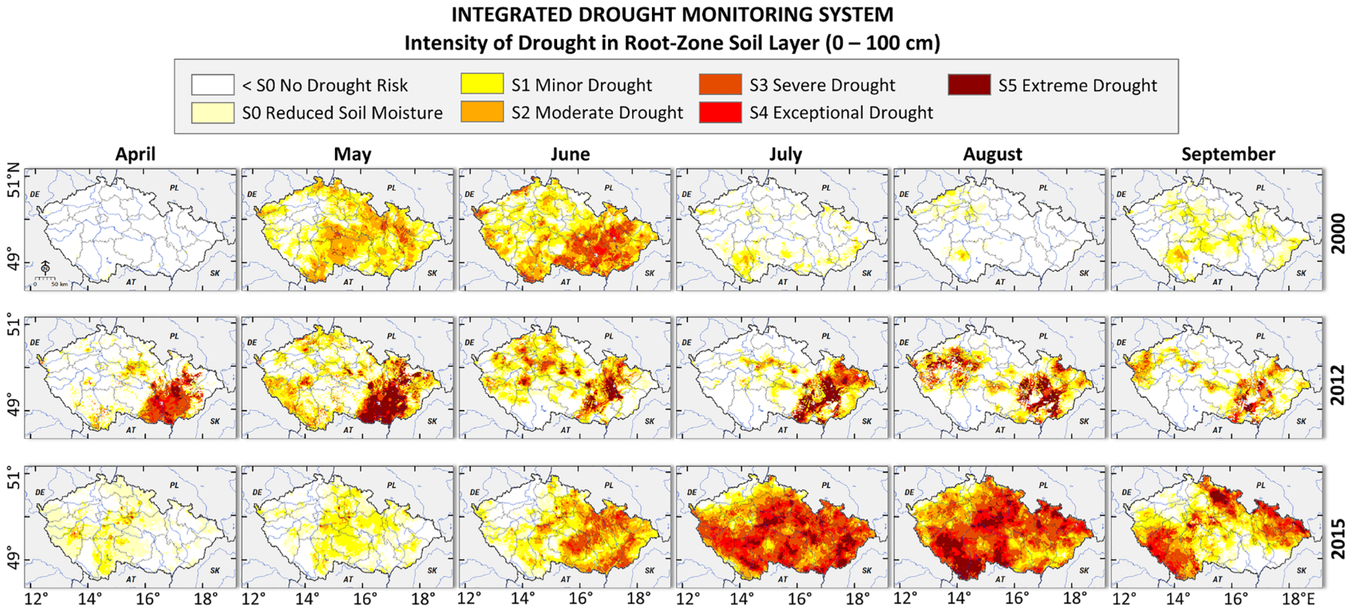


FIGURE 2 Monthly mean of the relative soil saturation (i.e. the percentage when the maximum soil moisture holding capacity is saturated) in the topsoil (0–40 cm) during the 2000, 2012 and 2015 vegetation seasons (i.e. April–September). Note: Wilting point = 0% and field capacity = 100%

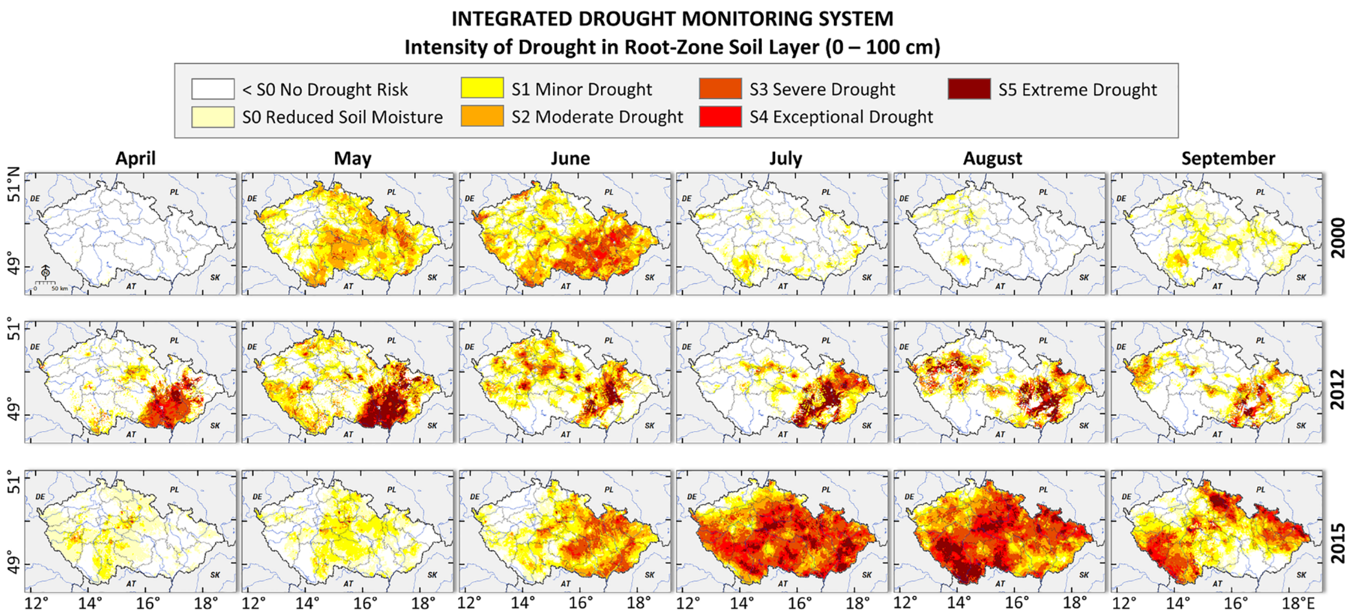


FIGURE 3 Intensity of drought expressed as an anomaly in the relative soil water saturation given the corresponding 21-day window from 1961 to 2010 reference period. The seasons during 2000, 2012 and 2015 are depicted by showing the early (2000) and late (2015) season droughts, as well as a local but highly persistent drought (2012). Table 1 is used to define the individual drought intensity categories

While the 2000 event hit more than two thirds of the country and severely affected the production of cereal and other field crops harvested during the July–August period, the drought was subtler and restricted in the southeast and central-eastern parts of the country. Figures 2 and 3 show how soil moisture anomalies persisted over several enclaves (Wagner *et al.*, 2013) during the entire growing period. In the four most affected LAU1 regions, a sharp decrease in winter and spring cereal yields to levels not seen since the 1960s occurred (Zahradníček *et al.*, 2015), while in neighbouring regions (even more so in the western two thirds of the country), a

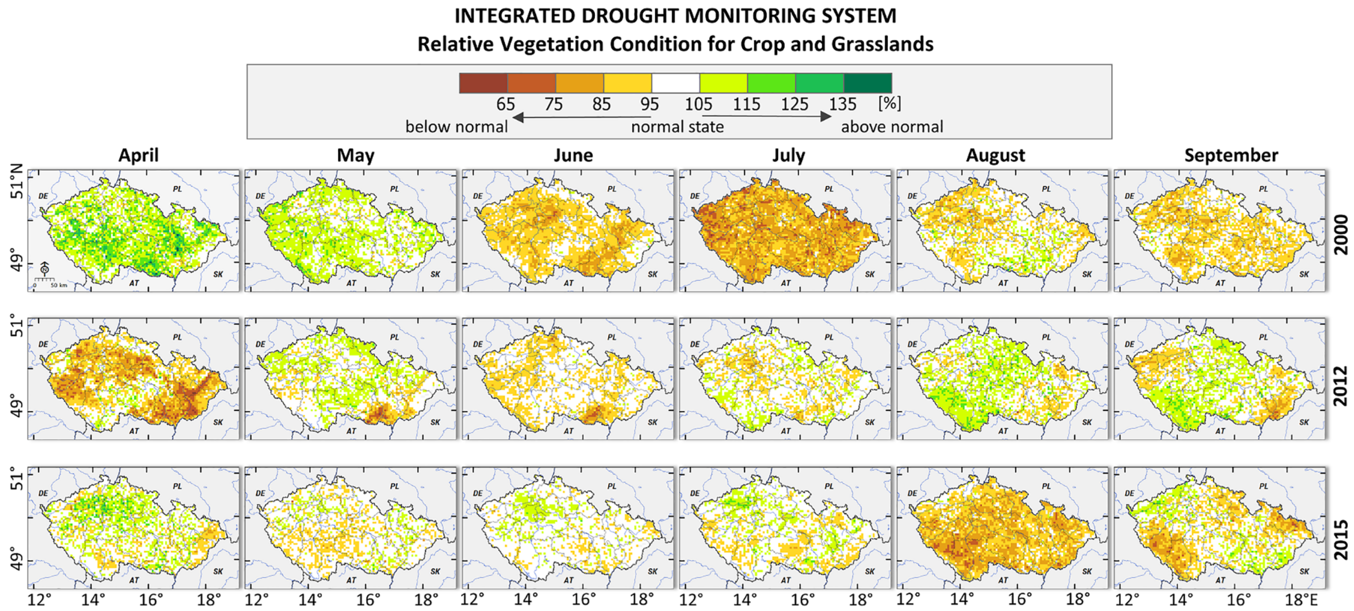
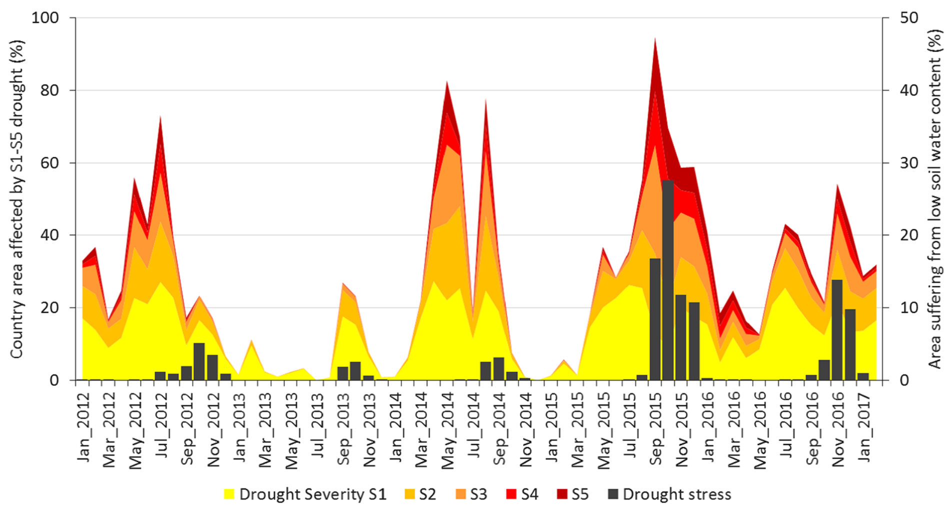


FIGURE 4 Relative vegetation conditions based on the EVI2 from the MODIS-Terra satellite and expressed as the 2000–2016 EVI2 anomaly. The original 250-m resolution data are aggregated into a 5 × 5-km grid

FIGURE 5 The left *y*-axis represents the area under drought (S1–S5 categories), while the right-hand *y*-axis shows the extent of the areas where the whole soil moisture profile is below 30% of the maximum water holding capacity



bumper crop was experienced. In 2015, over 90% of the country was under drought conditions, with 25% under exceptional drought conditions. The situation worsened after June (Figures 2 and 3) and peaked in August (Figure 5). This was followed by a massive vegetation signal decrease (Figure 4), which showed that the worst vegetation conditions occurred in August since 2000.

Compared to the 2012 event, when only a relatively small region was affected by notable drought impacts, the 2015 drought (Figures 2 and 4) started relatively late but affected the whole country in July and August. While cereal and oilseed rape yields were relatively high, crops that harvested later in the season, particularly maize and potatoes, suffered major yield declines. This was similar to the situation in Germany, where the 2015 drought was among the three worst droughts since 1961 in terms of duration and intensity (Zink *et al.*, 2016). The recognition of the CzechDM by users increased significantly during the 2015 event (Figure 5). While it had already received very good ratings during the 2014 drought period, in 2015, the information provided by the CzechDM became widely used for public information and drought assessments by local authorities. There were numerous requests for data from the Czech Ministry of Agriculture and the State Agricultural Intervention Fund, as well as the Agricultural Chamber of the Czech Republic. These entities used the CzechDM to inform agricultural and forest-related stakeholders about the current soil moisture status, and the maps were used as a source to calculate the damage and recovery support costs. The system received considerable public attention due to reports in several media outlets, which ranged from regional to national newspapers and included television broadcasters. The number of hits in 2014 (the first fully operational year of the CzechDM) included 29,506 page views by 4,304 individual users. This increased to 102,665 views by 20,545 users during the 2015 drought year and further increased to 237,917 views and 44,790 users in 2016. By end of July 2017, over 45,000 individual users viewed the pages over 215,000 times, equalling the visits in 2016 to that just within the first 7 months of the year in 2017. Between the start of the operation in 2014 and the end of 2017, there were over 690,000 page views and over 130,000 individual users.

We selected the 2017 drought episode to illustrate the current CzechDM procedure. As seen in Figure 5, the drought affected a significant portion of the country but not to the level reached in 2015. The effects of drought were quite severe, especially in the southeast and across many smaller regions in the west and southwest, while other parts of the country were not seriously affected. Despite this observation, the estimated losses reached over 120 million Euros within the farming sector alone. Figure 6 shows the situation during the week starting on July 2, 2017. The set of presented maps represent the key pieces of information that were used each week to estimate the drought status and impacts, which were then used to prepare weekly drought reports using the convergence of evidence approach. While Figure 6a,b indicates soil moisture anomalies in the topsoil and subsoil, Figure 6c indicates where the largest soil moisture deficit exists and that the soil profile contains up to 60 mm less water than in a normal year (i.e. 1 month of rainfall). The deficit was the largest in the eastern and north-central parts of the country. The ASCAT-based SWI (Wagner *et al.*, 1999) identified the lowest soil moisture content in the same regions, which confirmed the overall pattern based on the soil moisture model in Figure 6b. Ground-based reporting on soil moisture in the top 20 cm confirmed the pattern in Figure 6b,d again, with dry soils that were reported in the same regions as those where moderate to severe droughts were reported. Further signs of agricultural drought impacts can be particularly observed in the southeast region of the country (Figure 6f,h), where the most pronounced decline in vegetation conditions was noticed (Figure 6g). The reports on estimated drought impacts were cantered towards the southeastern region

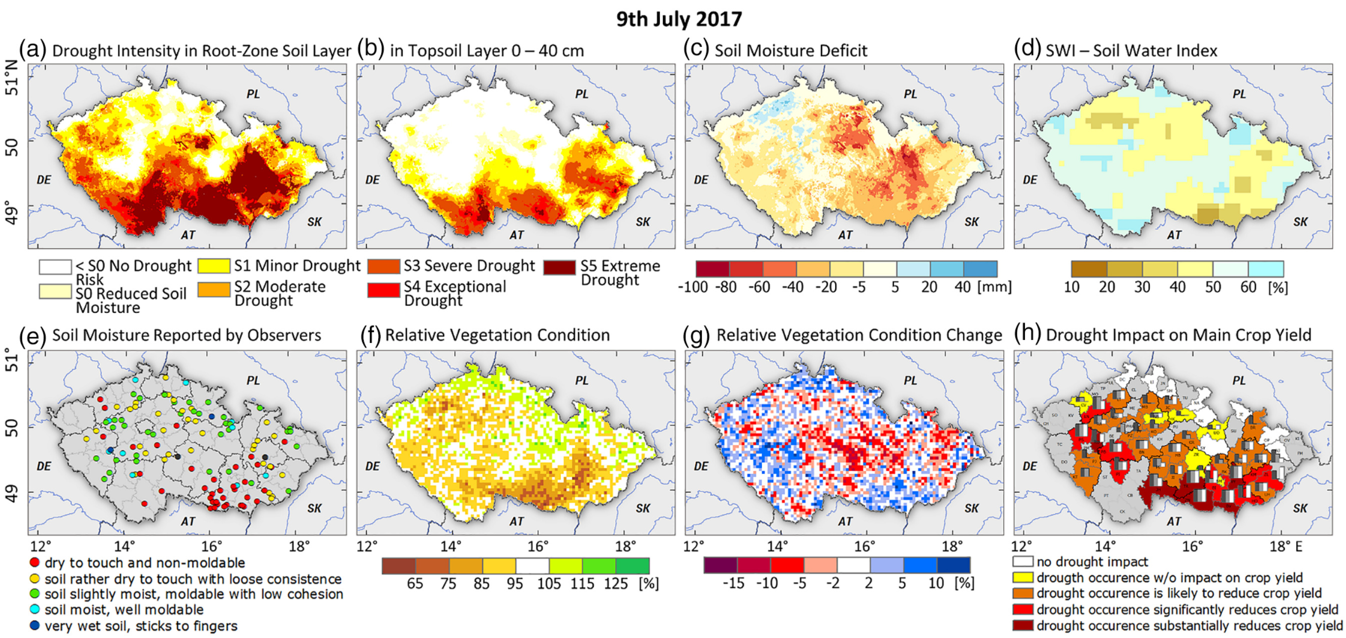


FIGURE 6 Peak in the 2017 drought episode in June–July of 2017 as detected by the CzechDM system on 9 July 2017: (a) soil moisture anomalies in the 0–1-m layer; (b) soil moisture anomalies in the topsoil (0–40 cm); (c) soil moisture deficits compared to usual values (mm); (d) independent ASCAT microwave radar estimates provided by TU Wien; (e) soil moisture in the topsoil as reported by drought reporters; (f) anomalies in the vegetation condition based on EVI2 data; (g) changes in the vegetation condition from the previous week; (h) expected overall impacts of drought on the crop yield levels estimated by drought reporters expressed by colour for LAU 1 units. The bars show how barley and wheat (left column), potatoes and sugar beet (central column) and maize (right column) crop yields are likely to be impacted

of the country (Figure 6h) as well, while other affected areas were located to the northwest (where drought conditions culminated approximately 2 weeks earlier). While this drought was reported from many regions by farmers and foresters, the impacts were fairly concentrated in the southeastern region of the country. The existence of the CzechDM allowed very precise drought assistance allocation based on the actual drought intensity and crop yield decrease at the cadaster level.

4 | RANKING THE MOST RECENT DROUGHT EPISODES

While users, stakeholders and the media require immediate responses to drought events, for appropriate actions to be taken, the magnitude of the drought and the likely impact must be interpreted based on experiences from past droughts (e.g. Wilhite and Pulwarty, 2017). Therefore, drought climatologies must also be assessed, and past events must be reviewed and compared in terms of drought characteristics and impacts. The CzechDM has been designed with the inherent ability to serve such a purpose, and example analyses of historical drought events are shown in Figure 7. Figure 7a uses the cluster identification algorithm proposed by Samaniego *et al.* (2013). This three-step algorithm, used, for example, by Zink *et al.* (2016), applies the duration, spatial extent and drought intensity of the event to calculate a dimensionless drought magnitude. The results show that the recent 2015–2016 drought event ranks among the top three longest events observed in the Czech Republic since 1961, but it certainly was not the most intense or longest event over the last 55 years. This event was surpassed in both characteristics by the 1983–1984 drought and especially by the 1973–1974 drought. The iconic 2003 drought that dominated drought rankings in large parts of Western Europe (e.g. Zink *et al.*, 2016) ranked fifth. More detailed insight can be obtained from the four panels on the right-hand side of Figure 7, which ranks the years according to the area under drought between 1961 and 2016. While the size of the bubble represents the intensity, the numbers next to the bubbles denote the respective year of the drought event. In terms of the combined July–August period, the 2015 drought likely ranked as the most severe or close to the most severe drought over the evaluated period, and it was still the fifth most intense drought during the month of September. Out of the five most intense drought years for each month during the June–September period, the years in the period beginning in 2000 were responsible for the top five spots in 10 out of the possible 20 events. The droughts in 2003 and 2015 had especially prominently features in this respect.

5 | DROUGHT FORECAST AND ITS VERIFICATION

For the CzechDM to provide more easily accessible agricultural drought information on both the regional and

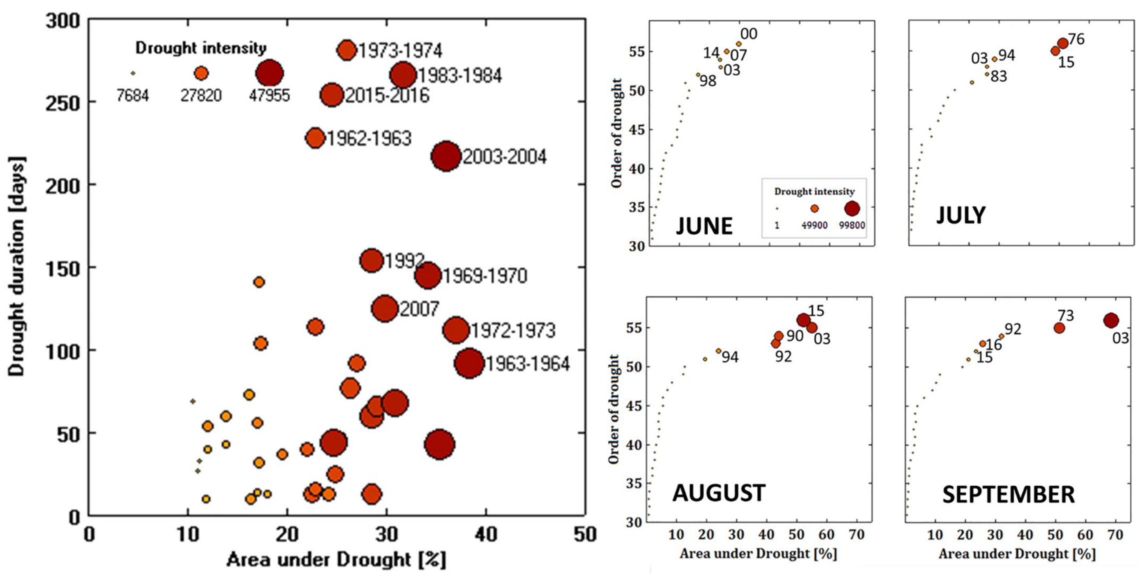


FIGURE 7 Ranked drought events during the 1961–2016 period. The panel on the left shows the relationships among the area, duration and intensity of drought events since 1961. The four panels on the right show the ranked drought areas during specific months over the last 62 years. The magnitudes are represented by the size of the bubble. The reference period for this figure is 1 January 1961 to 31 December 2016

national level, the forecasting module was added to its functionalities in 2016. It provides an added value through a daily, high-resolution forecast that was formerly inaccessible. Stakeholder feedback indicates that the main user groups derive from regional agencies, and the agricultural and forestry sectors especially appreciate the short-term drought forecasts, while the media seem to prefer longer-term outlooks based on statistical forecasts. During the smaller-scale 2016 drought, the CzechDM drought forecast was widely used by the media and stakeholders as the drought occurred. Figure 8 shows the performance of the forecasting ensemble models for a period of +1 to +9 days when using the February–May 2017 period.

The validation of the three drought characteristics (i.e., the difference between predicted and real drought values – AWP, relative soil saturation – AWR and soil moisture deficits – AWD) is presented in Figure 8 because they combine several meteorological elements. The drought prediction is evaluated on the basis of statistical characteristics such as bias and mean absolute error (MAE). The bias indicated whether the model systematically underestimated or overestimated the results, while the MAE indicated the magnitude of typical errors. In the case of AWP, the differences between the predicted and real mean droughts in the Czech Republic were compared. The difference between the real and predicted droughts was very low for all models. The largest mean difference only reached approximately the 0.6 AWP category (10%) for a 9-day forecast via the GFS model. The IFS provided by the ECMWF had the lowest error for a 9-day prediction. For the following day, the difference was only in the 0.1 category (2%); for the 9-day forecast, it was in the 0.5 category (8%). The best results for the 2–6-day forecasts were provided by the Global UM model. The ARPEGE and GEM models had slightly better performances than that of the GFS.

The second drought characteristic was AWR, which was expressed in terms of a percentage. The difference between the real saturation and the predicted one for the next day was lower than 1.2% for all models. For the 9-day prediction, the error was less than 4.2%. The best results were also provided by the Global UM and IFS models, and the least accurate model was the GFS and ARPEGE. For the 2–6-day forecasts, the Global UM provided a better prediction than that of IFS.

The final chosen drought characteristic was AWD, which was expressed in mm. For the next day, the absolute differences were very low, where the best performing models (IFS and Global UM) only had errors of approximately 1.4 mm. If we compared the longest duration models over 9 days, the best predictions were also provided by the IFS model, with an error of approximately 5.1 mm. The GFS had the least accurate forecast, with a

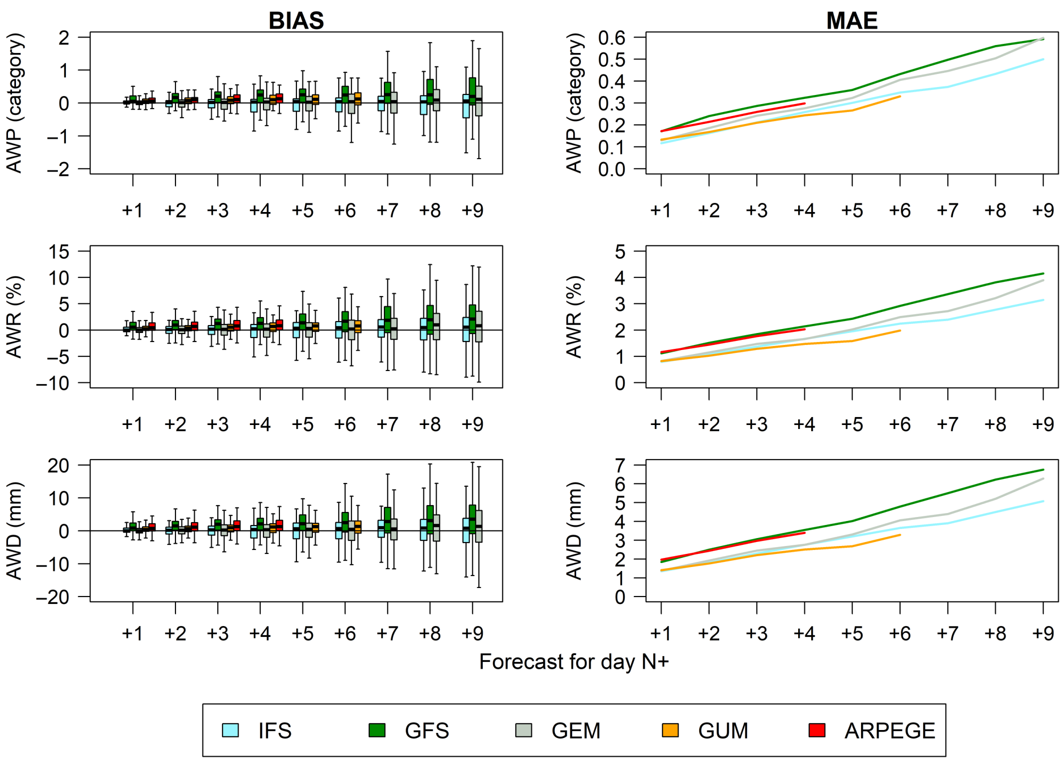


FIGURE 8 Comparison of five NWP model results for forecasts up 9 days for AWP, AWR and AWD, which are averaged across the entire Czech Republic. The values of the MAE and the systematic bias are shown

deficit of 6.8 mm for a 9-day forecast. Similar results were observed for the IFS for the 6-day GEM forecast.

The general conclusion is that the best forecast is provided by the Global UM and IFS models. The least accurate results are given by the GEM and ARPEGE models. The worst performing model from the selected ensemble is the GFS model. All models overestimate the results (the GFS has the greatest overestimation), which means that they have more soil moisture; however, in the case of the AWP drought category, a slightly higher drought value is predicted than the actual value. Nevertheless, the drought prediction, even for a 9-day forecast, is quite good, and the success rate for drought prediction is approximately 92% when the national level is considered.

The presented approached based on deterministic forecasts of individual numerical weather prediction models, performed significantly better than probabilistic forecast based on either IFS or GFS ensemble when tested during period 2016–2017. This has been true not only in case of drought forecasts but also agrometeorology and energy sector forecasts (Stepanek, Personal communication). While the CzechDM considers incorporation of subseasonal and seasonal forecasts many subsequent tasks need to be tackled including: (a) only air temperature and precipitation data are available and for consistency with operational forecast mode the CzechDM requires other meteorological variables in order to estimate evapotranspiration (primarily global radiation, air humidity and wind speed); (b) seasonal forecasts are provided as anomalies and not absolute values; (c) seasonal forecasts are and will be given as multimember ensembles which requires increased calculation intensity. Before these methodological discrepancies (between operational and long-term mode) are

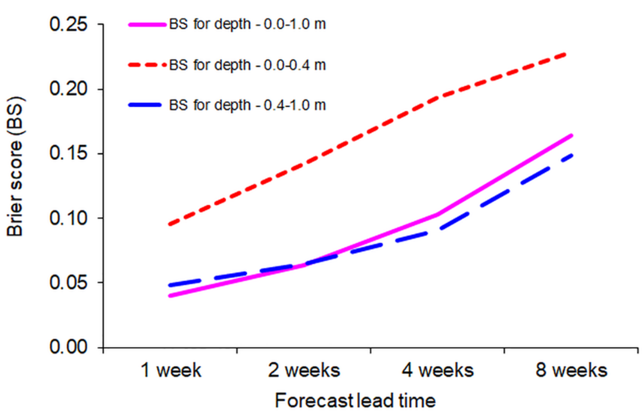


FIGURE 9 Comparison of Brier score for statistical forecast with 1, 2, 4 and 8 weeks lead times for whole soil profile (0–1 m) and to and lower soil layers based on the data from 2017 to 2018 seasons

thoroughly resolved the CzechDM applies a "simple" statistical approach (see Section 3.4).

To test the benefit of the statistical forecast of area affected by drought we used the BS, which was calculated in each grid cell and averaged over the area of the Czech Republic to show overall performance of the long-term forecast. Figure 9 illustrates lower predictability of the top soil layer using statistical forecast but quite reliable results for the drought years of 2017 and 2018. If we assume that the BS below 0.25 indicates applicable skill of the forecast compared to the climatology, then in the case of whole profile and the subsoil the results have been encouraging. They show that even for 8-week lead times the statistical forecast generated reasonable spatial drought patterns.

6 | CONCLUSIONS AND OUTLOOK

The CzechDM provides an easily accessible agricultural drought information system at local (i.e., cadasters) and national levels through the daily, high-resolution information. It uses a convergence of evidence approach by taking advantage of an existing high-density network of weather stations, remotely sensed data, and the participation of a network of reporters. Because some of the stakeholders (e.g. the State Land Office and the Agricultural Chamber of the Czech Republic) have provided guidance in the development of the system, it is driven by the requirements of the users. Stakeholder feedback indicates that the main user groups are from agricultural and forestry companies, governmental and regional agencies, the general public and the media. During the 2015 and 2017 drought events, the CzechDM was widely used by the media and stakeholders, particularly after drought consequences became obvious (e.g. crop or tree damage and low water levels). The CzechDM enables drought estimates at a higher spatial resolution (0.25 km^2) than other available products in the region, such as the European Drought Observatory (1 km^2) or the German Drought Monitor (16 km^2). A soil drought map for the Czech Republic is released to the public on a daily basis, with a lag of 1 day. A complete suite of products including satellite-based soil moisture estimates and vegetation conditions are released once a week with accompanying text summary on drought development over the past week in the Czech Republic and the wider region of Central Europe. The resume is written by the intersucho team. The complete weekly update of Pillars I, II and IV is carried out on Mondays and is accompanied by a text report. This is followed by a drought impact map (Pillar IV) based on the network of reporters, which is released every

Thursday. The forecasts for soil moisture content and drought severity for the next 9 days are also released daily to aid in operational decision-making by farmers and other users. The online archive allows for dynamic and fast access to the overview of drought events over the past 5 years, and all data since 1961 are available to users on request. The CzechDM information aims to support practitioners in optimizing their actions; hence, the role of forecasting is critical. The system has been used to provide national aid to companies (mostly farmers) affected by droughts in 2015 and 2017. It also provides the ability to operationally compare ongoing drought events to any event since 1961 in near real time, which also provides stakeholders the ability to estimate likely impacts based on past experiences. Currently, CzechDM data, particularly the vegetation condition component, are used to investigate the relationship between soil moisture, vegetation status and crop yield for different times of the year to gain more knowledge regarding the consequences of agricultural droughts. The aim is to forecast drought impacts during drought events to enable timely responses in the future. This might include the planned extensification of production by farmers (i.e., lowering the input intensity compared to the planned intensity level) during a drought event to reduce costs but also to lower the unnecessary use of fertilizers and pesticides. Currently, the CzechDM system has been also adopted by the Slovak Hydrometeorological Institute for drought monitoring in Slovakia. Key parts of this system are also being adopted by the DriDanube project for a drought impact forecasting system in the Danube basin.

Currently, the CzechDM resolution is 0.25 km^2, and research is being conducted to improve the resolution to 0.01 km^2 (i.e., 100×100 m). At this resolution, individual field blocks would be represented, and soil conditions and land use and terrain characteristics would also be taken into account with higher precision. However, such a shift requires a considerable increase in the calculation time and resources, and a cost–benefit analysis of such a move is currently being carried out. In order to complement the actual and reference evapotranspiration estimates based on the network of ground stations, the use of remote sensing based methods for estimation of actual evapotranspiration (ET_a) or ET_a/ET_r ratio, namely, ALEXI and ESI (Anderson *et al.*, 1997; Anderson *et al.*, 2011) is being tested. The CzechDM is operationally using these products starting from 2019 vegetation season (March–October). The CzechDM presented herein provides free, high-resolution, near real-time drought information for the Czech Republic and Slovakia and contributes to the mitigation of negative effects from agricultural droughts.

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