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Impact of data resolution on heat and drought stress simulated for winter wheat in Germany

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ABSTRACT

Heat and drought stress can reduce crop yields considerably which is increasingly assessed with crop models for larger areas. Applying these models originally developed for the field scale at large spatial extent typically implies the use of input data with coarse resolution. Little is known about the effect of data resolution on the simulated impact of extreme events like heat and drought on crops. Hence, in this study the effect of input and output data aggregation on simulated heat and drought stress and their impact on yield of winter wheat is systematically analyzed. The crop model SIMPLACE was applied for the period 1980–2011 across Germany at a resolution of 1 km × 1 km. Weather and soil input data and model output data were then aggregated to 10 km × 10 km, 25 km × 25 km, 50 km × 50 km and 100 km × 100 km resolution to analyze the aggregation effect on heat and drought stress and crop yield. We found that aggregation of model input and output data barely influenced the mean and median of heat and drought stress reduction factors and crop yields simulated across Germany. However, data aggregation resulted in less spatial variability of model results and a reduced severity of simulated stress events, particularly for regions with high heterogeneity in weather and soil conditions. Comparisons of simulations at coarse resolution with those at high resolution showed distinct patterns of positive and negative deviations which compensated each other so that aggregation effects for large regions were small for mean or median yields. Therefore, modelling at a resolution of 100 km × 100 km was sufficient to determine mean wheat yield as affected by heat and drought stress for Germany. Further research is required to clarify whether the results can be generalized across crop models differing in structure and detail. Attention should also be given to better understand the effect of data resolution on interactions between heat and drought impacts.

1. Introduction

Climate change will likely cause an increase in the frequency and magnitude of heat and drought stress during the winter wheat (*Triticum aestivum* L.) growing season across Europe (Semenov and Shewry, 2011; Gourdji et al., 2013). A higher frequency of extreme temperature episodes would result in more than one high temperature episode during the growth period (Ortiz et al., 2008). Higher mean and/or extreme temperatures during the growing season not only reduce photosynthesis rate, grain number and weight but also accelerate crop development and leaf senescence rate (Wheeler et al., 2000; Tubiello et al., 2007; Asseng et al., 2011). Heat stress mainly influences the reproductive phase of wheat (Ferris et al., 1998; Luo, 2011). In winter wheat, the number of grains remarkably decreased when the crop experienced temperatures larger than 31 °C immediately before anthesis (Wheeler et al., 1996). Also, it was found that the number of sterile grains of wheat significantly increased when temperature during mid-anthesis was larger than 27 °C (Mitchell et al., 1993). Short episodes of temperatures larger than 35 °C during the post-anthesis period reduced average grain weight of 75 Australian wheat cultivars by 23% (Stone and Nicolas, 1994). When mean temperature during grain filling was increased from 25 °C to 31 °C, final grain yield reduced by 15% through shortening of grain filling period (Dias and Lidon, 2009).

Drought is the most important limiting factor of wheat production across the world (Cattivelli et al., 2008). Effects of drought stress on wheat yield are determined by the severity and duration of the stress with a response that differs depending on the crop development stage (Rampino et al., 2006; Ji et al., 2010). Drought occurrence just before anthesis and during grain filling declined the number and weight of wheat grains, respectively (Prasad et al., 2011; Plaut et al., 2004; Dolferus et al., 2011; Rajala et al., 2009). Furthermore, drought stress influenced leaf area expansion, root

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growth, dry matter partitioning and photosynthesis rate (Jamieson et al., 1998).

Hot episodes during the growing season are often also dry and therefore, crops experience heat and drought stress often simultaneously (Halford, 2009). Previous research indicated that the effects of heat and drought stress on grain yield are hypo-additive, the effect of combined stress was higher than the individual effects but lower than their sum (Pradhan et al., 2012; Savin and Nicolas, 1996). Combination of drought and heat stress also resulted in higher leaf temperature and respiration than sole occurrence of heat or drought stress (Mittler, 2006).

To assess impacts of climate change and climate variability on crop yield at national or global scale, crop simulation models are increasingly used (Asseng et al., 2013; Lobell et al., 2011; Olesen et al., 2011) although, most of the crop models applied at large scales have been developed and parameterized at field scale (van Bussel et al., 2011a; Hansen and Jones, 2000). Because the density of weather stations is limited, large scale climate impact assessments are mostly forced with gridded weather or climate data interpolated between site measurements (e.g. Harris et al., 2013). Furthermore, large scale climate data often represent monthly means while crop models typically require daily values so that weather generators (e.g. Semenov et al., 2013) are used to increase the temporal resolution of the data. Alternatively, crop models are applied using measured weather data assuming that the obtained results for individual locations are representative for larger regions (Bannayan and Eyshi Rezaei, 2014). Similar to constraints in weather data, the heterogeneity in soil properties observed under field conditions is hardly reflected in large scale assessments.

Only recently, researchers started to study impacts of heat stress with crop models (Rötter et al., 2011; Asseng et al., 2013; Deryng et al., 2014; Teixeira et al., 2013). Aggregation or averaging of input variables from high to low resolutions decreases the variability of variables such as temperature (Diffenbaugh et al., 2005) but little is known about the necessity of using high resolution input data for (i) simulating large scale (regional or national) means of heat and drought stress and corresponding crop yields and (ii) for reproducing spatial variability of stress and crop yield.

The current study aims to systematically analyze the impact of data aggregation on winter wheat yields simulated across Germany for the period of 1980–2011 with the process based crop model SIMPLACE with a specific focus on the effects of heat and drought stress.

2. Materials and methods

2.1. General workflow of analysis

The analysis of the aggregation effect on heat and drought stress and yield involved several steps. A schematic diagram (Fig. 1) illustrates the flow of information and the different steps and types of data aggregation analysed. First, the crop model was evaluated against yield data reported by the agricultural statistics for the period 1999–2011 (Section 3.1). Then we aggregated model input data (climate, soil) from 1 km × 1 km resolution to the resolutions 10 km × 10 km, 25 km × 25 km, 50 km × 50 km, and 100 km × 100 km and analyzed the effects on frequency distributions and spatial patterns of climate and soil input data itself (Section 3.2) and the corresponding effect of this input data aggregation on heat and drought stress (Section 3.3) and crop yield (Section 3.5). Finally, we aggregated the model outputs calculated with high resolution input data to the resolutions 10 km × 10 km, 25 km × 25 km, 50 km × 50 km, and 100 km × 100 km and compared the corresponding heat and drought stresses (Section 3.4) and crop yields (Section 3.5) with simulations based on aggregated input data. By calculating differences between heat stress, drought stress and crop yield simulated at high resolution with results at aggregated resolution we analyzed the model specific systematic bias and the loss of spatial variability due to data aggregation across regions and the whole country (Sections 3.3–3.5).

2.2. Development of multi-resolution model input data

2.2.1. High resolution weather data

Daily values of minimum and maximum temperature, sunshine duration, humidity and wind speed for more than 1100 weather stations for period 1980–2011 were derived from the WebWerdis portal of the German Meteorological Service DWD (DWD, 2012a,b,c). In addition, the portal provided access to daily gridded precipitation at 1 km × 1 km resolution (Regnie data set) and to grids of monthly mean values of daily sunshine duration, daily minimum temperature, daily maximum temperature and daily mean temperature. These grids were developed by the DWD by interpolation of weather station data using a digital elevation model to support the interpolation (DWD, 2014). Daily values for temperature and sunshine duration $X_{\text{grid,d}}$ (°C) were computed for each 1 km × 1 km grid cell and for each day of the period 1980–2011 by using a procedure described in Zhao et al. (2015) as

$$X_{\text{grid,d}} = X_{\text{ws,d}} + X_{\text{grid,m}} - X_{\text{ws,m}} \tag{1}$$

where $X_{\text{ws,d}}$ was the daily value measured at the nearest DWD weather station, $X_{\text{grid,m}}$ was the monthly mean at the grid cell according to the 1 km × 1 km grid and $X_{\text{ws,m}}$ was the monthly mean at the nearest weather station. Use of this procedure ensured that the monthly mean value was equal to the value computed by the DWD for each grid cell in the 1 km × 1 km grid, while the day-to-day variation was equal to the variation reported for the nearest weather station (Siebert and Ewert, 2012). Daily solar radiation was then calculated from daily sunshine duration by using the Ångström–Prescott approach (Almorox and Hontoria, 2004). Extraterrestrial radiation was calculated according to Allen et al. (1998) while the Ångström coefficients a and b were computed by comparing, on sunny and overcast days, incoming shortwave radiation derived from satellite imagery to computed extraterrestrial radiation. Daily mean incoming shortwave radiation (W m^{-2}) and daily mean fractional cloud cover (%) were derived from the Satellite Application Facility on Climate Monitoring (CMSAF, 2012a,b) and analyzed for period 2005–2012. Daily wind speed was calculated by averaging daily mean wind speed across the weather stations of the DWD network. In total, 378 weather stations measured wind speed in period 1980–2011 but only stations with a measuring height of maximal 20 m above ground and an altitude of not more than 900 m. were considered when calculating the mean across stations, so that the number of stations considered in this study was 236. Measured wind speed was corrected to a sensor height of 2 m according to Allen et al. (1998) as

$$u_2 = u_s \frac{4.87}{\ln(67.8z - 5.42)} \tag{2}$$

where u_2 was the wind speed in 2 m height (m s^{-1}), u_s the wind speed at the sensor (m s^{-1}) and z the sensor height (m). The stations were selected because wind speed was measured there in an appropriate height and because the stations were located on or close to cropland. The calculation procedure resulted in wind speed that was similar for all grid cells in Germany but varied from day to day.

2.2.2. Soil properties at high resolution

Maximum rooting depth and volumetric water content at full saturation, field capacity and wilting point were derived from the