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LETTER

Intensity of heat stress in winter wheat—phenology compensates for the adverse effect of global warming

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Abstract

Higher temperatures during the growing season are likely to reduce crop yields with implications for crop production and food security. The negative impact of heat stress has also been predicted to increase even further for cereals such as wheat under climate change. Previous empirical modeling studies have focused on the magnitude and frequency of extreme events during the growth period but did not consider the effect of higher temperature on crop phenology. Based on an extensive set of climate and phenology observations for Germany and period 1951–2009, interpolated to 1 × 1 km resolution and provided as supplementary data to this article (available at stacks.iop.org/ERL/10/024012/mmedia), we demonstrate a strong relationship between the mean temperature in spring and the day of heading (DOH) of winter wheat. We show that the cooling effect due to the 14 days earlier DOH almost fully compensates for the adverse effect of global warming on frequency and magnitude of crop heat stress. Earlier heading caused by the warmer spring period can prevent exposure to extreme heat events around anthesis, which is the most sensitive growth stage to heat stress. Consequently, the intensity of heat stress around anthesis in winter crops cultivated in Germany may not increase under climate change even if the number and duration of extreme heat waves increase. However, this does not mean that global warning would not harm crop production because of other impacts, e.g. shortening of the grain filling period. Based on the trends for the last 34 years in Germany, heat stress (stress thermal time) around anthesis would be 59% higher in year 2009 if the effect of high temperatures on accelerating wheat phenology were ignored. We conclude that climate impact assessments need to consider both the effect of high temperature on grain set at anthesis but also on crop phenology.

1. Introduction

Trends of increasing mean temperature and extreme heat events during the last 30 years compared to previous centuries have frequently been reported [1–4]. There is also evidence for a more pronounced increase in temperature and for more frequent summer heat waves in Europe during the last decades [5, 6]. Global assessments suggest increasing heat stress on the world's cropland due to projected future climate change [7, 8], associated negative effects on crop yields [8] and a higher risk of hunger by 2080 when accounting for climate change effects [9]. Already in the recent past, the global impact of increasing temperature has reduced world wheat production by 4.9% between 1980 and 2008 in relation to a counterfactual without climate trends [10, 11]. Understanding and modeling the effects of temperature, including heat stress, on crops is still limited and prone to large uncertainties [12–14]. Empirical evidence about long-term trends of heat stress and related effects on crops is therefore urgently required to support such understanding and to improve future yield projections.

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 [15, 16]. The wheat plant is mainly sensitive to heat stress around anthesis and during the grain filling period [17, 18].

Evaluation of the heat stress effect around anthesis is a particular challenge due to its specific nature, whereby effects on grain yield can already be observed as a result of short episodes of high temperature [19]. In addition, our understanding of the processes and relationships involved in heat stress effects on crops are mainly obtained under controlled environment conditions, with little understanding about their relevance under field conditions. The general assumption is that heat stress around anthesis results in fewer grains, causing the reported yield reduction [20]. The number of grains falls when the crop experiences temperatures above 31 °C immediately before anthesis [21]. It was also found that the number of sterile grains of wheat can significantly increase when temperature during mid-anthesis is above 27 °C [22].

Several studies have suggested a substantial increase in the frequency and magnitude of heat stress effects on wheat production due to climate change for different parts of Europe [23–26]. Some of them explicitly investigated possible adaptation strategies against increasing heat stress [27]. However, most of these studies have been conducted by using statistical models which did not consider changes in crop phenology caused by global warming. Earlier onset of phenological phases in the spring period may result in a cooling effect and compensate therefore for the effect of global warming on the intensity of extreme heat around anthesis. In contrast, most process-based crop models can reproduce changes in crop phenology due to increasing temperature [28] but little is known on how changing phenology affects crop heat stress intensity. In this study we analyze observations to derive (i) trends in spring temperature for German cropland and period 1951–2009, (ii) related changes in the timing of the period around anthesis, (iii) trends in the intensity of heat stress around anthesis, and (iv) the effect of changes in crop phenology on the intensity of heat stress around anthesis.

2. Materials and methods

2.1. Preparation of temperature data

Daily values of minimum, mean and maximum temperature for more than 1100 weather stations and interpolated grids of monthly means of daily minimum, mean and maximum temperature at 1 × 1 km resolution for the period 1951–2009 were obtained from the WebWerdis portal of the German Meteorological Service DWD [29]. Daily values for minimum, mean and maximum temperature $X_{\mathrm{grid,d}}$ (°C) were computed for each 1 × 1 km grid cell and for each day of the period 1951–2009 by using a procedure described in [30] as

$$X_{\mathrm{grid,d}} = X_{\mathrm{ws,d}} + X_{\mathrm{grid,m}} - X_{\mathrm{ws,m}}, \qquad (1)$$

where $X_{\mathrm{ws,d}}$ is the daily value measured at the nearest DWD weather station (°C), $X_{\mathrm{grid,m}}$ is the monthly mean at the grid cell according to the 1 × 1 km grid (°C) and $X_{\mathrm{ws,m}}$ is the monthly mean at the nearest weather station (°C). 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 × 1 km grid, while the day-to-day variation was equal to the variation reported for the nearest weather station [30]. A cropland mask that is based on the Corine land cover 2006 [31] was applied to the 1 × 1 km daily temperature grids [30] to mask out areas with natural vegetation, forests or grasslands (often located in mountainous regions) and to ensure that mean values calculated across the 1 × 1 km grid cells are representative for cropland. To identify impacts of global warming on day of heading (DOH) we calculated, for each year, the mean temperature for the period March–May which reflects roughly the period between winter dormancy and anthesis. Hourly temperature, required for calculation of heat stress (described in section 2.3), was calculated from daily maximum and minimum temperature by applying a sine function [32].

2.2. Preparation of phenology data

Observations of the DOH of winter wheat were collected by the phenological observation network of the German Meteorological Service and derived from the DWD WebWerdis portal [29] for the period 1951–2009 and filtered for potential outliers as described in [33]. The total number of observations after applying the filtering process was 80 831 obtained from 5456 sites across Germany.

There were no observations for Eastern Germany for the period 1961–1990. To fill this gap, we estimated DOH of winter wheat by using continuous DOH observations for winter rye obtained from the same source and filtered for outliers using the same method. For each DOH observation of winter rye in Eastern Germany we calculated the median of differences between DOH of winter wheat and winter rye for observations obtained in Western Germany, constrained to a region varying not more than ±0.5° in latitude and ±50 m in altitude from the location in Eastern Germany (figure 1). This resulted in 14 368 additional records for DOH of winter wheat in Eastern Germany for the period 1961–1990. 5805 records obtained for the periods 1951–1959 and 1991–2009 were used to validate this method by comparison of estimated DOH for winter wheat with the observed DOH. We found a high accuracy, with an RMSE of 1.8 days and a R^2 of 0.81 for the annual means of observed and estimated differences between heading days of winter wheat and winter rye (figure 1), but less agreement for specific observations with an RMSE of 8.3 days.

The final data base for DOH of winter wheat contained 95 199 records from 5465 locations but the number of observations differed considerably across years and locations, with most observations for the

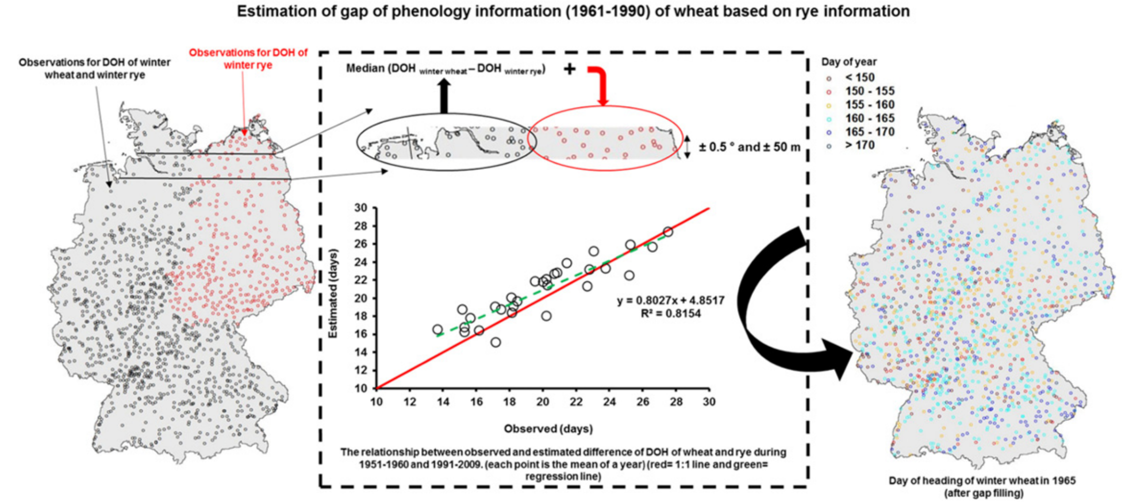

Figure 1. The workflow of the generation of 'day of heading' data of winter wheat to fill the data gap for East Germany and period 1961–1990. It schematically describes the data processing based on the difference in observed phenology of winter wheat and winter rye in West Germany. It also shows the 1:1 plot between estimated and observed difference between day of heading of winter wheat and winter rye during the 29 years for which the dataset was complete.

year 1958 (2100) and the least number in 2007 (336). There was no observation site with complete data coverage for the period 1951–2009.

To obtain uniform data coverage for the whole period, the records for DOH were interpolated for each year to a 1×1 km grid by using inverse distance weighting as the interpolation method. The development rate of winter wheat shows a strong response to temperature and day length in the period before flowering (anthesis) so that higher temperature and long day conditions should result in an earlier DOH [34, 35]. To account for the effects of temperature and day length on DOH we performed, for each year separately, a multivariate regression of altitude (affecting temperature) and latitude (affecting mainly day length) on DOH (step 1 in figure 2). The regression equations were then used to correct all observations to mean sea level and 50.81°N, the mean latitude of all observations (step 2 in figure 2). Then the corrected observations were interpolated to 1×1 km resolution and added to another 1×1 km grid that contained, for each grid cell, the difference in DOH caused by the cell specific altitude and latitude calculated from the regression equation for the specific year (step 3 in figure 2). We performed this procedure to account in the interpolation for the spatial variability in temperature and day length between the observation sites and the corresponding effect on DOH.

2.3. Analysis of heat stress around anthesis of winter wheat

Stress thermal time around anthesis of winter wheat STT_{27} (°C min) was calculated as an indicator for heat stress by accumulating hourly temperatures T_h (°C) above the critical threshold T_{crit} (°C) for a three-week period around anthesis, starting one week before anthesis:

$$STT = \sum 60 \text{ Max}\left(T_h - T_{crit};\, 0\right). \quad (2)$$

The critical temperature threshold for heat stress around anthesis is about 31 °C [18] but for this study we used a threshold of 27 °C to account for differences between measurements of air temperature at 2 m height (used for this study) and higher canopy temperature indicated for rainfed wheat in Germany [14]. A sensitive period of three weeks was selected to account for the local variability of heading dates due to different crop management, mainly sowing date.

2.4. Trend analysis

Visual inspection of time series of mean temperatures for the period March–May and mean DOH calculated across all grid cells indicated a break point in the temperature and DOH trends with very little trend in the first period but strong trends in the second period. Therefore, segmented, piecewise linear regression of DOH and temperature on year was performed [36]. For both variables, a breakpoint was determined in 1976. Therefore, we distinguished in all subsequent analyses the periods 1951–1975 and 1976–2009 and determined, at grid cell level and for the mean across all grid cells, linear trends for mean temperature, DOH and STT_{27} for both periods. The segmented, piecewise linear regression was also performed to determine a breakpoint in the mean number of days with a daily maximum temperature >27 °C throughout Germany, which was found to occur in 1987. To determine the specific effect of changes in crop phenology on heat stress, the time series for DOH and the period 1976–2009 was de-trended for each 1×1 km grid cell as:

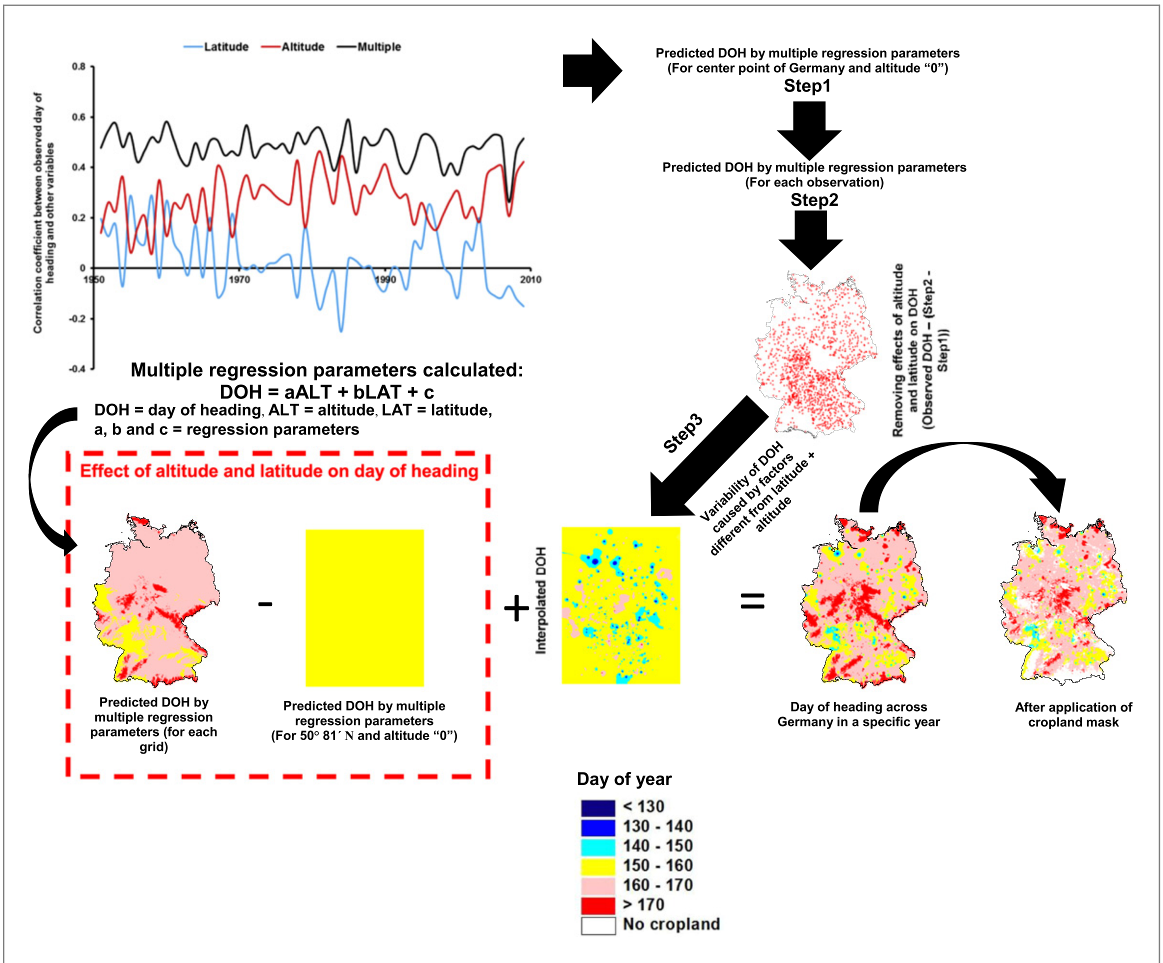

Figure 2. The stepwise workflow of the interpolation of day of heading to 1 × 1 km resolution across Germany by accounting for the effects of latitude and altitude on day of heading.

$$\mathrm{DOH}_{\mathrm{detrended,grid}} = \mathrm{DOH}_{\mathrm{observed,grid}} - (\mathrm{year} - 1975) \times \mathrm{trend}, \quad (3)$$

where $\mathrm{DOH}_{\mathrm{detrended,grid}}$ was the de-trended day of heading (day of the year), $\mathrm{DOH}_{\mathrm{observed,grid}}$ was the observed day of heading (day of the year), year the actual year and trend the trend in DOH for period 1976–2009 determined by linear regression of DOH on year. Heat stress STT_{27} was then recomputed with the de-trended DOH and compared to STT_{27} calculated with the observed DOH.

3. Results

There was a remarkable increase in mean temperature from March to May in the period 1976–2009 as compared to the period 1951–1975 across the whole country (figure 3(a)). Areas of high temperature (>8.9 °C) extended from the former hot spots in the Rhine valley to all the lowlands in Central and Southern Germany (figure 3(a)). Mean temperature (March–May) calculated across all grid cells had a slight negative trend (Trend = −0.005 °C yr^{-1}, $R^2 = 0.001$) from 1951 to 1975 and a strong positive trend (Trend = 0.060 °C yr^{-1}, $R^2 = 0.31$) from 1976 to 2009 (figure 3(a)). The negative trends for mean temperature from 1951 to 1975 were only detected in the Southern part of the country, while for the period 1976–2009 an increasing trend (0.04 to > 0.07 °C yr^{-1}) was found in all grid cells of the country (figure 3(a)). The mean number of days with daily maximum temperature >27 °C calculated across Germany increased by 0.01 d yr^{-1} from 1951 to 1987 but by 0.05 d yr^{-1} in the period 1988–2009 (SI figure 1).

For most regions in Germany, DOH was mainly in mid to late June during the period 1951–1975 but advanced to late May to mid-June over the period 1976–2009 (figure 3(b)). There was a minor change in DOH from 1951 to 1975 (Trend = 0.08 d yr^{-1}, $R^2 = 0.02$). In contrast, a strong advancement in DOH (Trend = −0.44 d yr^{-1}, $R^2 = 0.51$) was observed from 1976 to 2009 (figure 3(b)). The trend in DOH showed a clear difference between the Northern and Southern part of Germany during the first period (1950–1975). However, the trend to earlier DOH was almost the same throughout the country for the period 1976–2009 (−0.4 to < −0.6 d yr^{-1}) (figure 3(b)). A high year-to-year variability in DOH was observed across Germany but at the same time years with very early DOH became much more frequent, particularly in the last two decades (SI video 2).

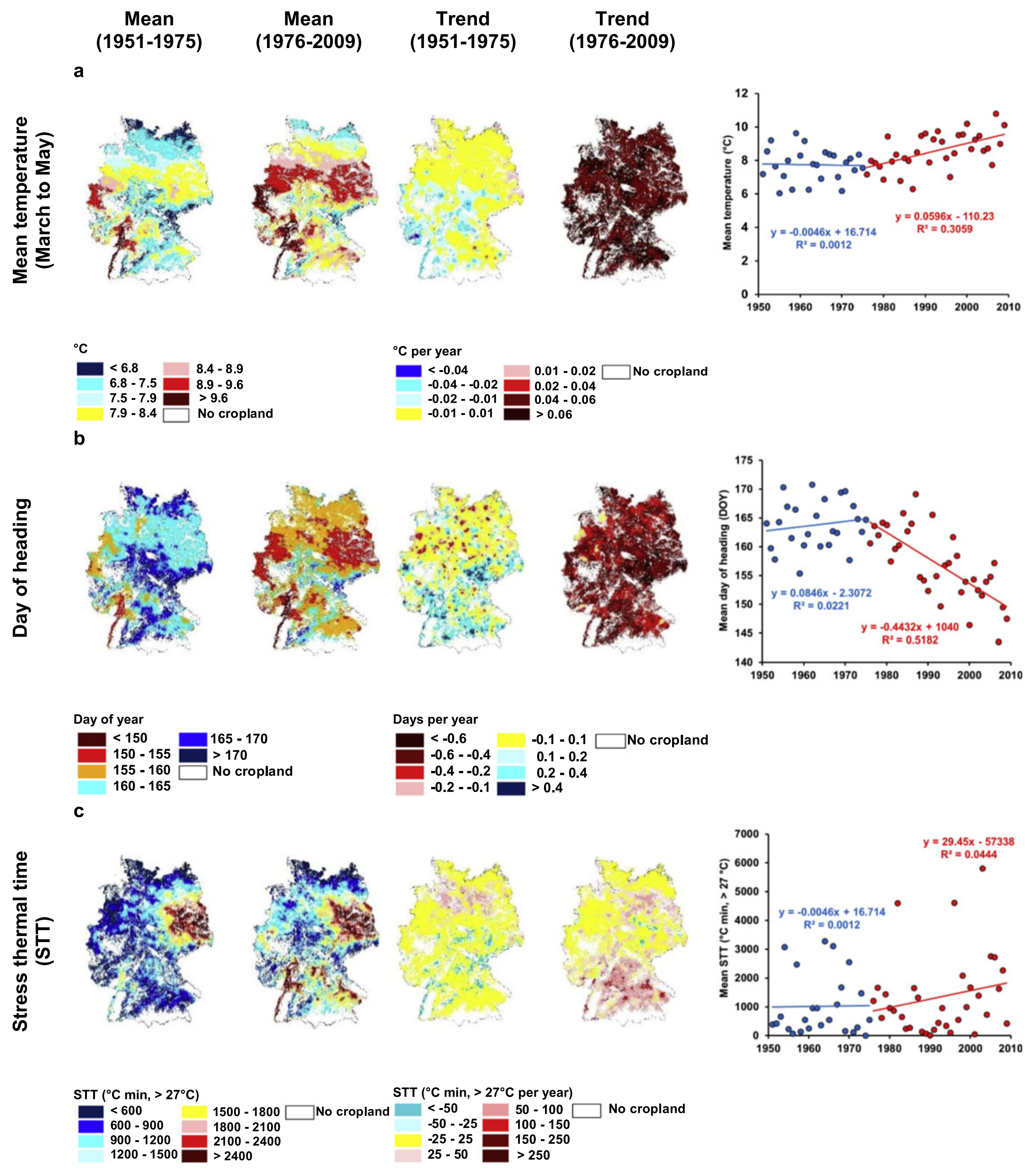

Figure 3. Spatial pattern of mean and trend for periods 1951–1975 and 1976–2009 at 1 × 1 km resolution for the mean temperature for the period March–May (a), mean day of heading (b) and mean stress thermal time (STT) (c) across Germany.

There was no notable difference in heat stress between the two periods except for the Southern part of Germany where an increasing trend in STT_{27} was detected for the period 1976–2009 (figure 3(c)). Therefore, hotspots of heat stress with mean STT_{27} above 2100 °C minute extended from the Southern part of Eastern Germany to river valleys in Southern Germany (figure 3(c)). There was no obvious trend in STT from 1951 to 1975 (Trend = −0.004 °C min, >27 °C, $R^2 = 0.001$) but a slight increasing trend from 1976 to 2009 (Trend = 29.45 °C min yr^{-1}, $R^2 = 0.044$) (figure 3(c)). In any case, the strong increasing trend of mean temperature from March to May (figure 3(a)) did not translate into large increases of heat stress in the period around anthesis (figure 3(c)).

We also analyzed the trend of mean temperature (March–May), DOH and STT_{27} for heat-prone areas with a mean STT_{27} of more than 2000 °C min in the period 1951–2009 and found similar results (SI figure 3). Mean temperature and DOH varied between 6.3 °C and 11.8 °C and mid-May to end of the June, respectively across Germany (SI figure 3). The trend to earlier DOH in the period 1976–2009 was quite similar (−0.47 d yr^{-1}) in heat prone areas (SI figure 3) as compared to the whole country (−0.44 d yr^{-1}) (figure 3(b)). Furthermore, the trend of mean temperature (0.056 °C yr^{-1}) and STT (29.12 °C min, >27 °C) showed almost no difference between heat-prone areas and the whole country (figure 4(a), figures 3(a) and (c)).

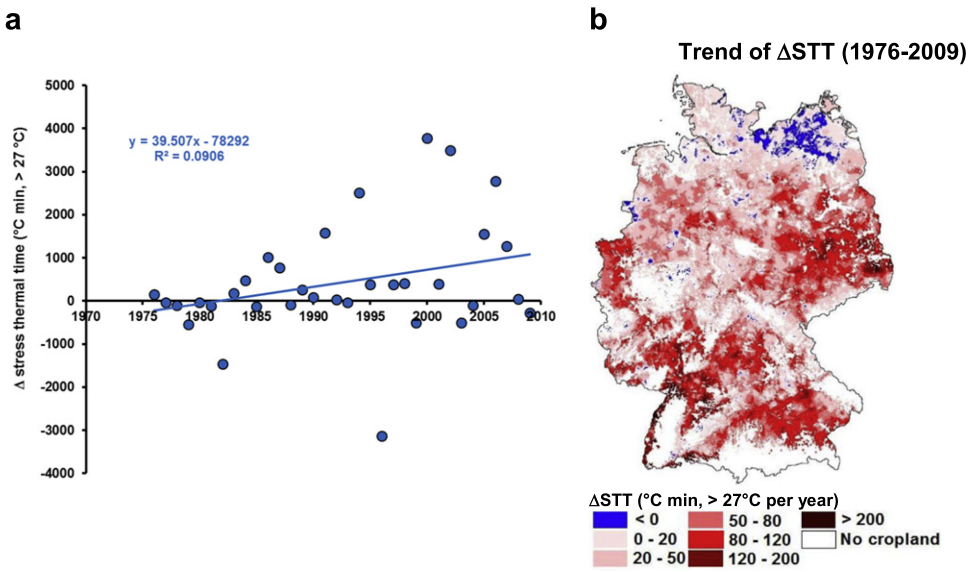

Figure 4. Heat stress avoided due to earlier heading of winter wheat. *Δ*STT (stress thermal time calculated with de-trended day of heading—stress thermal time calculated with observed day of heading) shown as mean across cropland in Germany (a) and as map showing the trend in *Δ*STT (b) for period 1976–2009.

Calculating STT_{27} for the period 1976–2009 with de-trended DOH resulted in more heat stress, in particular for the latest 15 years. Consequently, there was a strong positive trend (39.507 °C min) in the difference between heat stress calculated with de-trended DOH and heat stress calculated with observed DOH (figure 4(a)). Based on the trends for period 1976–2009, STT_{27} around de-trended anthesis day would be 59% higher in year 2009 than STT_{27} around the observed anthesis day. A positive difference in the trend of heat stress calculated with de-trended DOH and that calculated with observed DOH was found for almost all grid cells in Germany (figure 4(b)). Some exceptions in the data along the coastline or at the national border may be artifacts of the interpolation procedure, which did not consider data outside Germany. The results suggest that the trend to earlier DOH observed for the period 1976–2009 (figure 3(b)) and the corresponding shift of the period around anthesis towards the cooler spring season, compensated almost completely for the warming trend (figure 3(b)) so that heat stress around anthesis increased only slightly (figure 3(c)).

4. Discussion

Our findings that DOH of winter wheat advanced in recent decades in parallel with an increase in the air temperature in spring is in good agreement with results from previous studies. For example, significant changes in plant phenology have been detected in response to temperature increase across 19 European countries [37]. The length of the growing period and the period from emergence to heading of oats (*Avena sativa* L.) for the period 1959–2009 across Germany fell by 14 or 8 days, respectively [33].

While there is evidence for the change in crop phenology, it is more difficult to find the reasons for the changes. Many studies suggest a close link between changes in crop phenology and changes in temperature during the growing season. For example, simulation of wheat phenology under expected future climate change suggested that the crop development rate will accelerate due to effect of higher temperature, causing a two-week advancement in anthesis for 2060 compared to the present across 14 diverse sites across Europe [38]. The advancement of DOH in winter wheat found in this study may therefore be explained by the 2 °C increase in mean temperature (March–May) at the same period over Germany (figure 3(a)). We found a strong relationship between temperature rise and advancement of phenology (SI figure 4(a)), in line with other studies.

The slope of the increment in mean temperature against DOH showed a relatively homogenous pattern across Germany (figures 3(a) and (b)). However, changes in DOH could also be determined by changes in preceding phenological stages including day of sowing (DOS). We therefore compared the trends in the observations for DOH of winter wheat with observations for DOS and day of emergence (DOE) and based on the equations of the piecewise regressions (SI figure 4(b)) we estimate that DOS, DOE and DOH have advanced by 5.1, 4.2, and 13.2 days in period 1951–2009. This indicates that the major change in crop phenology happened in the phase between emergence and heading which is also supported by the increasing mean temperature in this phase (SI figure 4 (d)). This means that the cooling effect due to the shift of the phase towards the spring could not fully compensate for the increase in temperature due to global warming, which is similar to the results found in another study on oats [33].

Changes in crop phenology could also be caused by changes in cultivar properties. An indicator for systematic changes in the maturity type of cultivars is the change in the temperature sum above the base temperature T_b. Temperature sum above the base temperature, set to 0 °C in the phase between emergence and heading, showed a small increasing trend (SI figure 4(e)) but at the same time, the mean day length in the growing period before heading declined due to the shift of the heading day into the spring season (SI figure 4(f)). Since the development rate of wheat declines in response to shorter day length [2], this decline in day length will offset the effect of increased temperature sum, suggesting only very little change of cultivars used in Germany with regard to their phenological properties.

The small increase in STT_{27} from 1976 to 2009 (figure 3(c)) could also be caused by an increase in variability of temperature. STT_{27} responds to high temperature but not to low temperature extremes (equation (2)). Therefore, increase in variability may lead to a positive trend in STT, even when the mean temperature remains the same. In fact, we only found a very small increase in mean temperature in the period around anthesis (SI figure 5) while there was a very extreme heat stress event in year 2003 (6000 °C min, >27 °C, figure 3(c)). Based on German agricultural statistics [39] the lowest winter wheat yield from 1994 to 2009 was observed in that year with a reduction of 20% in comparison to the year with the highest yield.

The analysis presented here was constrained to the period around anthesis, but heat stress can also reduce crop yield in the subsequent grain-filling period [40]. However, the critical temperature threshold for heat stress in the grain-filling period is higher [18]. Therefore we think that for German climatic conditions, heat stress around anthesis may be more relevant. However, since the grain-filling period is typically also finished before the beginning of the hottest period of the year, an advance in crop phenology would have a similar effect on heat stress during grain filling as shown in this study for the phase around anthesis. More research is however required to test this hypothesis. Similarly to this, the relationship between heat stress and crop phenology needs to be tested for other regions and crops. We expect similar effects for crops for which maturity falls in the season of increasing temperature, e.g. other winter cereals. In contrast, there is likely very little potential to escape heat stress by accelerated phenological development for spring sown crops like maize that are harvested in autumn and grow through the hottest period of the year. The effect of advanced flowering date in a cooler part of the season is not likely to be relevant for crops grown in tropical climates either, in which temperature variability throughout the year is very low.

We show in this study that the length of the period between emergence and heading has declined over the period 1976–2009 in Germany. Very likely, this has also reduced winter wheat yields because plant canopies have less time to intercept radiation which is needed to produce biomass by photosynthesis. Therefore, other studies suggested that farmers need to adapt [41], e.g. by growing cultivars with higher thermal requirements and later maturity [42]. We show in this study that such an adaptation would expose the crop to more heat, while the accelerated phenological development protected winter wheat in recent decades to a large extent from the harmful effects of heat stress. Therefore, the potential to adapt to climate change by changing sowing dates and cultivars may be more limited than previously thought [10, 25].

Finally, our results suggest that studies attempting to analyze and project heat stress effects on crops should not only consider effects of heat on grain number and yield but also need to account for changes in the phenological development caused by higher temperature to avoid misleading conclusions. This is in particular important when the adaptation of crop production to climate change is investigated by empirical models.

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