Response of rice phenology to climate warming weakened across China during 1981–2018: did climatic or anthropogenic factors play a role?

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Abstract

Climate warming has substantially shifted plant phenology, which alters the length of growing season and consequently affects plant productivity. Recent studies showed a stalled or reversed impact of climate change on vegetation phenology since 1998, as well as an asymmetric warming effect. However, how field crop phenology responded to the recent climate warming and the asymmetric warming remains unknown. In addition, the relative roles of climate change, sowing date and cultivars shifts in the spatiotemporal changes of crop phenology at different regions need to be better understood. Here, using the latest 9,393 phenological records at 249 agro-meteorological stations across China over 1981–2018, we critically investigated the spatiotemporal dynamics of rice phenology and disentangled the effects of different drivers by exploiting the physiological relationship between crop phenology and thermal accumulation. The results showed that length of growing period (GP) increased by 3.24 ± 0.15 days/decade for single rice, 1.90 ± 0.22 days/decade for early rice and 0.47 ± 0.14 days/decade for late rice. Although climate warming during rice GP did not slow down, the trends in rice GP and the correlations between GP and temperature decreased generally from 1981–1999 to 2000–2018. The weakened phenological response to climate change was mainly caused by agronomic managements, especially cultivar shifts. Climate warming shortened GP by 0.84 ± 1.80, 1.23 ± 0.77, and 1.29 ± 1.24 days/decade for single rice, early rice and late rice, respectively. However, cultivar shifts prolonged it respectively by 3.28 ± 3.68, 2.15 ± 2.38, and 2.31 ± 3.36 days/decade, totally offsetting the negative effects of climate warming. Rice responded to daytime and night-time warming differently with night-time temperature affecting GPs more. Our study provided new insights that rice phenology responded to night-time warming more than daytime warming across China however the response to climate warming weakened, and cultivar shifts outweighed climate change in affecting rice phenology.

1. Introduction

Phenological stages, which are strongly controlled by short- and long-term variability in climate, have been the first-observed biological footprint of climate change impact (Piao et al 2019, Ettinger et al 2020, Wu et al 2021). Global warming has greatly shifted the timing of plant phenological events, altered the length of the growing season, and consequently affected ecosystem structure, function and their climatic feedbacks (Liu et al 2016, Piao et al 2017, Vitasse et al 2018).
Crop phenology has great ecological and economic implications, considering its great biophysical influences on land surface heat and water fluxes, the dominant harbor of biodiversity and the close relation to crop productivity (Challinor et al. 2014, Zhao et al. 2017, Asseng et al. 2018). Crop systems are valuable natural laboratories for exploring ecosystem’s response and adaptation to climate change, especially for such complicated and highly heterogeneous environments in China. Comparing with more concerns on forest or grass, and consistent results on natural ecosystems (Vitasse et al. 2018, Wu et al. 2018, 2021, Meng et al. 2020, Ettinger et al. 2020, Rosbakh et al. 2021), crop phenology is more complex because it is subject to both natural and anthropogenic factors (Tao et al. 2012, 2014, Abbas et al. 2017, Hu et al. 2017). For example, climate warming can advance crop phenology and shorten growth duration, but agronomic management such as sowing date and cultivar shifts may offset the negative impacts to some extent (Tao et al. 2012, 2014). In addition, crop phenology is also complicatedly affected by many other factors such as photoperiod and vernalization (Tao et al. 2012, 2014, Zhang et al. 2014a, He et al. 2015, Rezaei et al. 2017, Wang et al. 2017a, Ortiz-Bobea et al. 2021). Attributing the changes in the phenology is thus exceptionally challenging. Nevertheless, understanding the phenological dynamic and its underlying drivers is essential for crop management, crop growth monitoring and production prediction, as well as developing climate change adaptation options (Tao et al. 2006, Siebert and Ewert 2012, 2013, Sánchez et al. 2014, Shew et al. 2020).

Recently, some studies showed a stalled or reversed impact of climate warming on plant phenology since 1998 (Fu et al. 2015, Ballantyne et al. 2017, Güsewell et al. 2017, Piao et al. 2017, Wang et al. 2019c). For example, Fu et al. (2015) showed that the sensitivity of spring leaf unfolding to climate warming decreased by 40% from 1981–1994 to 1999–2013 using long-term observations for seven dominant European tree species. Wang et al. (2019c) showed no trends in spring and autumn phenology globally during 1998–2012. Empirical evidence for this, however, is limited to natural vegetation. Whether climate warming during crop GP slows down, and how field crop phenology responds to such warming remains unclear. In addition, many studies have evaluated crop phenological response to temperature, but few of them explicitly have investigated which temperature variable, i.e. daily mean \( T_{\text{mean}} \), night-time \( T_{\text{min}} \) or daytime \( T_{\max} \) temperature, play a dominant role (Tao et al. 2013, 2014, Piao et al. 2017, Wu et al. 2018, 2021). The increase rate of \( T_{\text{min}} \) over the past five decades was 1.4 times that of \( T_{\max} \). This asymmetric warming was reported to have contrasting effects on the timing of autumn plant phenology in the Northern Hemisphere (Peng et al. 2013, Wu et al. 2018). Yet how field crops phenology responded to the asymmetric warming remains unclear. Moreover, most of previous studies have focused on estimating the effects of climate variables (He et al. 2015, Gao et al. 2018), but few studies have quantified the contributions of agronomic practices to the phenological shifts in specific regions (Abbas et al. 2017, Hu et al. 2017, Rezaei et al. 2017, Wang et al. 2017a). The few available analyses have rarely taken the mechanical processes into account and not thoroughly investigated the effects of different drivers such as climate, sowing date, cultivar thermal requirement and photoperiod sensitivity. The analyses focused on the influences of anthropogenic management have mostly conducted on the observations before 2013 (Tao et al. 2006, Siebert and Ewert 2012, Tao et al. 2014, Zhang et al. 2014a, Parent et al. 2018). Crop phenological responses to recent climate warming and its regional disparity have not yet been well documented, especially in China.

Previous studies have mainly used statistical or process-based models to characterize sensitivity of phenology to climate warming and to isolate the contribution of different drivers (Tao et al. 2014, Wang et al. 2017a). The results on the impacts of climate change on crop phenology were inconsistent, which showed climate change shortened (Tao et al. 2012, Abbas et al. 2017) or prolonged (Zhang et al. 2014a, Hu et al. 2017) crop growth period (GP) or had insignificant effects on it (Wang et al. 2017a, Tariq et al. 2018, Ye et al. 2019). Such divergent results may be ascribed to the limited ground observations with coarse spatiotemporal resolution or different analysis methods. With few ground observations, it is difficult to separate the impacts of climate change and agronomic practices on crop phenology by statistical methods (Zhang et al. 2013, de Los Campos et al. 2020). Alternatively, crop model can be applied to investigate the mechanisms on and quantify the contributions of different drivers to crop phenology changes (Jones et al. 2003, Muller et al. 2017, Xin and Tao 2019, Zhang et al. 2020). Yet calibrating crop model with limited field trials and then applying them for the studies over long-term or broad regions will inevitably cause large uncertainties (Asseng et al. 2013, Li et al. 2015, Rezaei et al. 2018). In complement, integrating the two methods on the basis of accumulated thermal development unit, a well-known horticultural principle, provides a promising way to obtain more robust estimations (Lobell and Asseng 2017, Laskin et al. 2019, Peng et al. 2020).

Along this line, in this study, we collected the latest rice phenology dataset including 9,393 phenological records at 249 agro-meteorological experiment stations across China over 1981–2018. Based on the largest dataset on rice phenology so far, we integrated the statistical methods and crop model simulations to (a) investigate the spatiotemporal dynamics
of rice phenology over the past four decades, as well as the differences between 1981–1999 and 2000–2018; (b) identify the key temperature variables controlling rice phenology using the updated climate observations at 2459 meteorological stations; (c) disentangle the roles of climatic and anthropogenic factors in rice phenology change.

2. Material and methods

2.1. Rice phenology and climate observation data

Data on the observation of transplanting, heading and maturity date from 1981 to 2018 were obtained from the national agro-meteorological experiment stations across the entire rice cultivation areas in China. The phenological dates were observed and recorded by well-trained agricultural technicians in the experimental field and then checked and managed by the Chinese Agricultural Meteorological Monitoring System. It was the latest dataset with the longest time series and the most observational stations for rice phenological events in China. Only the stations with more than 15 years of records were used for analysis, with 9393 phenological records at 249 observational stations. Rice cultivation areas were classified into five agricultural ecosystem zones (AEZs), according to climate, topography, hydrography, soil, geology and cropping systems (figure 1). Details on the cropping system, number of stations and mean date in each AEZ are shown in table 1 and supplementary figure S1 (available online at stacks.iop.org/ERL/17/064029/mmedia). The daily weather data on $T_{\text{mean}}$, $T_{\text{max}}$ and $T_{\text{min}}$ were obtained from 2459 meteorological stations across China, which were obtained from the National Meteorological Data Center (http://data.cma.cn/).

2.2. Calculating temperature and ADTU during rice GP

Rice GP is defined as the duration from transplanting to maturity, which is divided into the vegetative growing period (VGP, from transplanting to heading) and the reproductive growing period (RGP, from heading to maturity). Average temperature during VGP, RGP and GP was calculated at each station in a year.

Accumulated thermal development unit (ATDU) refers to the photo-thermal requirement of a certain cultivar to reach a specific development stage, which represents the comprehensive characteristic of a cultivar including thermal requirements and photoperiod sensitivity. Trend in ATDU thus represents the effects of cultivar shifts on the phenology. ATDU is calculated as the methods used by cropping system model-CERES-Rice in Decision Support System for Agrotechnology Transfer 4.7 (Jones et al 2003, Hoogenboom et al 2019). ATDU is the sum of daily thermal development unit during VGP and the sum of daily thermal time (DTT) during RGP.

$$ T_{\text{max}} \leq T_{\text{base}} \text{ or } T_{\text{min}} \geq T_{\text{high}} $$

$$ T_{\text{max}} > T_{\text{opt}} \text{ or } T_{\text{min}} < T_{\text{base}} $$

$$ T_{\text{max}} > T_{\text{opt}} \text{ or } T_{\text{min}} < T_{\text{base}} $$

$$ \text{DTT} = \begin{cases} \sum_{h=1}^{24} (T_{\text{he}} - T_{\text{base}}) & \text{if } 0, \\ \frac{24}{T_{\text{max}} + T_{\text{min}}} - T_{\text{base}}, & \text{if } T_{\text{he}} > T_{\text{base}} \text{ and } T_{\text{he}} < T_{\text{base}} \end{cases} $$

$$ T_{\text{he}} = \begin{cases} T_{\text{base}}, & \text{if } T_{\text{h}} < T_{\text{base}} \\ T_{\text{opt}}, & \text{if } T_{\text{h}} > T_{\text{opt}} \\ T_{\text{h}}, & \text{others} \end{cases} $$

$$ T_{\text{h}} = \frac{T_{\text{max}} + T_{\text{min}}}{2} + \frac{T_{\text{max}} - T_{\text{min}}}{2} \times \sin \left( \frac{3.14}{12} \times h \right) $$

$$ \text{DTDU} = \text{DTT} \times \text{DF} $$

$$ \text{DF} = \begin{cases} 1, & \text{if } DL \leq P2O \\ \left[1 + \frac{P2O}{13} \times (DL - P2O)\right]^{-1}, & \text{if } DL > P2O \end{cases} $$

where $T_{\text{min}}$ and $T_{\text{max}}$ are daily minimum and maximum temperature, $T_{\text{base}}$ is the lower limit and $T_{\text{high}}$ is the upper limit at which rice suffered tissue injuries. $T_{\text{opt}}$ is the optimal temperature giving the highest rate of rice physiological process. $T_{\text{h}}$ is hourly temperature and $T_{\text{he}}$ is effective temperature in h hour in a day. DF is a photoperiod factor, P2R is photoperiod sensitivity parameter, P2O is the critical day length. DL is mean day length and estimated as a function of latitude and day of the year (DOY) at a station using the R package geosphere. The parameters in the above formulas (table 1) were obtained from Zhang et al (2014a).

2.3. Disentangling the effects of climate change and agricultural managements on rice phenology

We first defined the average of ATDU and transplanting date from 1981 to 1983 as referenced cultivar (ATDU$_{\text{ref}}$) and transplant date (transplanting$_{\text{ref}}$), respectively. We then estimated heading and maturity
Figure 1. Spatial distribution of agro-ecological stations in each agricultural ecosystem zone for rice. MLRYR: middle and lower reaches of the Yangtze River.

Table 1. Details on the cropping system, number of stations and mean transplanting date as well as the parameters for calculating ATDU (Accumulated Thermal Development Unit) in each AEZ for rice.

| Zone | Number of stations | Rice type | Mean transplanting date | T_{base} (°C) | T_{opt} (°C) | T_{high} (°C) | P2R | P2O |
|------|---------------------|-----------|--------------------------|----------------|-------------|--------------|-----|-----|
| I    | 16                  | Single rice | 15 May–27 May            | 8.36           | 27.24       | 38.47        | 77.23 | 12.81 |
| II   | 23                  | Single rice | 1 June–20 June           | 9.35           | 27.26       | 38.61        | 21.75 | 11.76 |
| III  | 18                  | Single rice | 14 April–27 May         | 8.64           | 26.5        | 39.67        | 151.9 | 12.86 |
| IV   | 29                  | Single rice | 5 April–1 June          | 8.82           | 27.82       | 37.82        | 64.47 | 11.66 |
| V    | 46                  | Early rice  | 1 June–20 June          | 11.84          | 31.08       | 40.24        | 22.19 | 11.75 |
| VI   | 24                  | Late rice   | 15 May–27 May           | 9.82           | 27.87       | 40.12        | 103.98 | 11.98 |

Date for each data series using (figure 2): (E1) fixed cultivar (ATDU_{ref}) and fixed transplanting date (transplanting_{ref}) and the observed transplanting date; (E2) fixed transplanting date (transplanting_{ref}) and the observed cultivar (Tao et al. 2014, Hu et al. 2017, Wang et al. 2017a). For case E1, we first accumulated DTT from a given developmental stage (e.g. transplanting) to the next stage (e.g. heading) using the ATDU_{ref} as a criterion. The date was recorded when the accumulated DTT reached the ATDU_{ref}. The length of GP was denoted as GP_{E1}. Trend in the time series of GP_{E1} was ascribed to the effect of climate change. We similarly estimated GP_{E2} and GP_{E3}. Trend in the difference between GP_{E2} and GP_{E1} (ΔGP_{trans}) was ascribed to changes in transplanting date. Trend in the difference between GP_{E3} and GP_{E1} (ΔGP_{cult}) was attributed to cultivar shifts. Trend in the observed GP was ascribed to the joint roles of climate and agricultural managements. The residuals between the trends in the observed GP and GP_{E1}, GP_{E2} and GP_{E3} were ascribed to the role of other factors such as fertilization and irrigation. In addition, the effects of all agricultural managements together on rice phenology were estimated as the differences between the trends in the observed GP and GP_{E1}.

2.4. Statistical analysis

We first performed piecewise regression with two linear segments to detect the potential turning point in the time series of temperature (T_{mean}, T_{max} and T_{min}), phenological events (transplanting, heading and maturity) and GPs (VGP, RGP and GP). Since the turning point for all variables appeared around 1999 (supplementary figure S2), we divided the 38 years into two 19 year periods: 1981–1999 and 2000–2018.
An independent-sample t-test was tested the difference between the two time periods. Trends in the phenological events, GPs and temperatures were examined using linear regression. Partial correlation analyses were conducted to determine the relationship between rice GPs and three temperature variables. Two-tailed t-test was used to test the significant level. Statistical analyses were implemented using R 4.0.3 and Stata 13.

3. Results

3.1. Spatiotemporal changes of rice phenology
In the past 38 years, rice phenological dates advanced at more than half of the stations, although there were remarkable differences among rice types, AEZs and time periods (figure 3). Transplanting date advanced significantly at 50% of the stations for early rice, followed by single rice (43%) and late rice (30%) (figure 3(a)). Transplanting dates of single rice advanced in zone IV during 1981–1999, and the advancement moved northward to zone II and III during 2000–2018 (figure 3(b)). Transplanting dates of early and late rice delayed in all the AEZs in 1981–1999, whereas advanced in the zones with the earlier transplanting in 2000–2018 (figures 3(c) and (d)). Different spatiotemporal patterns of the trends were observed for heading date (figure 3(e)). Heading date of single rice delayed by around 0.18 ± 0.13 days/decade (figure 3(f)). Heading date of early rice advanced in zone V (−1.20 ± 0.45 days/decade) whereas delayed in zone VI (1.70 ± 0.97 days/decade) during 1981–1999, and delayed consistently in both zones (0.14 ± 0.30 days/decade) during 2000–2018 (figure 3(g)). The trend for late rice was similar to that for early rice, but with relatively great degree (0.81 ± 0.28 days/decade) (figure 3(h)). In contrast, maturity dates of all the three rice types consistently delayed across AEZs during the two periods (figures 3(i)–(l)), especially for early rice (the average of 2.23 days/decade), followed by single rice (1.54 days/decade) and late rice (1.18 days/decade).

3.2. Changes in length of rice GP and their relations to different temperature variables
Rice GP lengthened at most stations however depending on rice types and studied periods. The trends decreased generally from 1981–1999 to 2000–2018 (figure 4). Rice GP increased significantly at 56%, 46% and 24% stations for single, early and late rice, respectively (figure 4(a)). Single rice GP increased across AEZs during the two time periods (figure 4(b)), especially for zone II (>4 days/decade). Early rice GP behaved similarly as single rice, but with a smaller magnitude (figure 4(c)). In contrast, late rice GP shortened during 1981–1999 whereas lengthened during 2000–2018 (figure 4(d)). Rice VGP significantly lengthened at more than 30% stations (figure 4(e)). Single rice VGP lengthened in the three AEZs in southern China during the two time periods (figure 4(f)). The trends reversed totally from 1981–1999 to 2000–2018 for early and late rice (figures 4(g) and (h)). Rice RGP significantly lengthened at 43% stations for single rice, followed by early (26%) and late rice (12%) (figure 4(i)). The RGP lengthened in almost all AEZs during the two periods for all the three rice types (figures 4(j)–(l)).

Under the intensified climate warming in the past four decades, $T_{\text{max}}$ increased more than $T_{\text{mean}}$ and $T_{\text{min}}$ for single rice whereas $T_{\text{min}}$ increased more for early and late rice (supplementary figure S3). Rice GP was generally affected more by $T_{\text{min}}$ than $T_{\text{max}}$ and $T_{\text{mean}}$ for all the rice types (figure 5). The GP was negatively correlated with $T_{\text{min}}$ at 89% stations (figure 5(a)), with the highest correlation coefficient for single rice, followed by early and late rice (figures 5(b)–(d)). $T_{\text{max}}$ was also negatively correlated with the GP in most AEZs (figures 5(e)–(h)). However, it was positively correlated with single rice GP in zone II and III during 1981–1999 and zone IV during 2000–2018. In contrast, $T_{\text{mean}}$ affected rice GP
less independently of rice types, AEZs and time periods (figures 5(i)–(l)). Collectively, climate warming during rice GP did not slow down significantly from 1981–1999 to 2000–2018 (supplementary figures S2 and S3); however both the trends in duration and the correlation coefficients between duration and temperature were generally decreased from 1981–1999 to 2000–2018, indicating that responses of rice phenology to climate warming weakened.

3.3. Effects of climate warming and agricultural managements on rice GPs

Once disentangling the contributions of different drivers, we found that climate warming negatively, cultivar shifts positively, and transplanting date changes and the other factors such as fertilization and irrigation weakly affected the VGP, RGP and GP, although the impacts varied by rice types and studied periods (figure 6). For single rice, increased temperature reduced GP by $\sim$0.57 days/decade whereas cultivar shifts increased GP by more than 2.53 days/decade during 1981–2018 (figures 6(a), (d) and (g)). Transplanting date changed GP by $-0.15$ and $0.10$ days/decade during 1981–1999 and 2000–2018, respectively. For early rice, temperature decreased VGP by 1.51 days/decade whereas increased RGP by 0.57 days/decade, leading to a decrease of GP by 0.94 days/decade during 1981–1999 (figures 6(b), (e) and (h)). During 2000–2018, increased temperature negatively affected both VGP and RGP, leading to a decrease of GP by 0.63 days/decade. Similarly, for single rice, cultivar shifts increased GP by more than 1.5 days/decade during the two periods, and transplanting date and other factors had small

Figure 3. Spatial patterns of trends in rice transplanting date (a)–(d), heading date (e)–(h) and maturity date (i)–(l) during 1981–2018. The stations with a trend significant at $P < 0.05$ are marked by +. Heat maps of (b), (f) and (j) (single rice), (c), (g) and (k) (early rice), (d), (h) and (l) (late rice) show zone-specific trend and standard deviation (in brackets) across all stations during three time periods and difference in its absolute value between 1981–1999 and 2000–2018. The trends and differences that are statistically significant at the level of 0.1, 0.05, and 0.01 are marked by *, **, and ***, respectively.
Figure 4. Spatial patterns of trends in GP (a)–(d), VGP (e)–(h) and RGP (i)–(l) for rice during 1981–2018. The stations with a trend significant at $P < 0.05$ are marked by +. Heat maps of (b), (f) and (j) (single rice), (c), (g) and (k) (early rice), (d), (h) and (l) (late rice) show zone-specific trends and standard deviation (in brackets) across all stations during three time periods and difference in its absolute value between 1981–1999 and 2000–2018. The trends and differences that are statistically significant at the level of 0.1, 0.05, and 0.01 are marked by *, **, and ***, respectively.

impacts on GP by <0.5 days/decade. For late rice, GP decreased by 0.58 days/decade during 1981–1999 because of the integrated impacts of cultivar shifts which shortened VGP by −2.24 days/decade whereas lengthened RGP by 1.23 days/decade, and climate warming which lengthened RGP by 0.45 days/decade (figures 6(c), (f) and (i)). During 2000–2018, however, the observed GP was increased by 1.31 days/decade owing to the integrated impacts of cultivar shifts (1.96 days/decade), climate warming (−0.71 days/decade), and shifts in transplanting dates and other agronomic managements. Overall, the growth cycle was prolonged for all the three rice types during both the periods, despite of the negative effects of warming. This was mainly because agronomic managements, especially cultivar shifts, outweigh climate change in affecting the GP changes (figure 7).

4. Discussion

4.1. The declined rice phenological response to climate change

We showed that climate warming did not slow down significantly during rice GP (supplementary figure S3) but the phenological responses declined generally from 1981–1999 to 2000–2018 (figures 3–5). The decline was largely because agronomic managements, especially cultivar shifts, dominantly controlled the GP trends (Tao et al 2013, Zhang et al 2014a, Wang et al 2017a, Ye et al 2019). Climate warming generally advanced the phenology and shortened the GP, whereas cultivar shifts compensated or reversed the negative effects (figure 6). Yet this compensation effect was reduced from 1981–1999 to 2000–2018 because the rate of cultivar...
Figure 5. Partial correlation coefficient between temperatures and length of rice GP during 1981–2018. The stations with correlation significant at $P < 0.05$ are marked by +. Heat maps of (b), (f) and (j) (single rice), (c), (g) and (k) (early rice), (d), (h) and (l) (late rice) show zone-specific correlation coefficient and standard deviation (in brackets) across all stations during three time periods and difference in its absolute value between 1981–1999 and 2000–2018. The correlation coefficients and differences that are statistically significant at the level of 0.1, 0.05, and 0.01 are marked by *, **, and ***, respectively.

renewal decreased (Challinor et al 2016, Watson et al 2018, Kahiluoto et al 2019) and the shifts in transplanting date weakened (figures 3(b)–(d)). Besides anthropogenic factors, other mechanisms may also play a role, such as the ‘photoperiod limitation’ mechanisms (Fu et al 2015, 2019, Meng et al 2020). This was demonstrated by the negative correlation between day length and ATDU requirements for all the rice types (figures 8(a)–(c)), suggesting that the decreased day length (supplementary figure S4) may decelerate rice development rate thus limit the phenological advancement when the events occur too early in the season. This study reveals that rice phenological response to climate change declined across China, suggesting that rice phenology may continue to advance with climate warming but the rate may slow down. The results show that anthropogenic managements outweigh climate warming in affecting rice phenology, highlighting that climate change impact studies should adequately account for anthropogenic adaptation.

4.2. The different effects of daily mean, daytime, and nighttime warming on rice phenology

Our analyses showed that rice phenology responded differently to $T_{\text{min}}$, $T_{\text{max}}$ and $T_{\text{mean}}$, and $T_{\text{min}}$ affected more significantly the GPs for all the three rice types, which was well supported by chambers and field-based studies in cereals across major cropping regions of the world (Peng et al 2004, Impa et al 2021, Schaarschmidt et al 2021, Sakai et al 2022). The stronger negative effects of $T_{\text{min}}$ may mostly result from its greater increasing rate (supplementary figure S3). According to equation (1), the low
temperature could become above the base temperature with climate warming and then start to affect rice development and phenology. In addition, $T_{\text{min}}$ is negatively correlated with standardized precipitation evapotranspiration index (SPEI) in dry temperate regions (Peng et al. 2013, Wu et al. 2018), a stronger drought (i.e. a low SPEI) may affect rice growth negatively and consequently lead to an earlier phenology event. A lower pollen viability and pollen germination percentage caused by night-time warming was noticed in rice (Jain et al. 2007, Mohammed and Tarpley 2009, Zhang et al. 2018). An additional mechanism to interpret the negative effects of $T_{\text{min}}$ may be that $T_{\text{min}}$ is generally positively correlated with autotrophic respiration and evapotranspiration (Wang et al. 2017b, Su et al. 2018, Lian et al. 2020). That is, elevated $T_{\text{min}}$ could enhance autotrophic respiration, reduce soil moisture availability and indirectly limit the duration of photosynthesis during the following daytime. Moreover, increased night-respiration and reduced photosynthesis by higher night-temperature is significantly higher during the post-flowering stage comparing with pre-flowering stage in rice, which will negatively affect grain-filling
duration, post-flowering senescence and grain protein composition (Peraudeau *et al* 2015, Bahuguna *et al* 2017, Impa *et al* 2021). That is why RGP is more sensitive to night-time warming than VGP (supplementary figures S4 and S5).

For the advanced phenology and shortened GPs associated with \( T_{\text{max}} \), it is mainly because rising \( T_{\text{max}} \) could reduce photosynthetic activity through enhancing evaporation and reducing soil water content (Schlaepfer *et al* 2017, Reich *et al* 2018, Samaniego *et al* 2018). There is observational evidence that \( T_{\text{max}} \) is negatively correlated with soil water content retrieved from multiple microwave satellite sensors in dry temperate regions (Owe *et al* 2008). Furthermore, a higher \( T_{\text{max}} \) is always associated with stronger radiation and potentially a higher chance of water stress (Piao *et al* 2017, Wu *et al* 2018, 2021). By contrast, \( T_{\text{min}} \) affected the phenotype less and even had a slightly positive correlation with the GPs (figure 5), implying rice growth is more vulnerable to extreme temperatures, especially night-time warming. Therefore, the effects of \( T_{\text{min}} \) on crop phenology need to be paid more attention to.

### 4.3. The roles of climatic or anthropogenic factors in affecting rice phenology

After disentangling the effects of climatic or anthropogenic factors, we found the factors controlling crop phenology varied by growth stages and studied periods. In 1981–1999, changes in temperature shortened GP for early rice, prolonged GP for late rice, and impacted less on GP for single rice, which were consistent with many previous studies using statistical approaches (Tao *et al* 2013, Zhang *et al* 2014a, Hu *et al* 2017, Ye *et al* 2019) and crop model simulations (Zhang *et al* 2016a, Wang *et al* 2017a). In 2000–2018, however, increase in temperature consistently shortened rice GPs, implying a totally different adaptation strategy (figure 6). During 1981–1999, the cultivars with a longer GP (higher ATDU requirements) were adopted for single rice (supplementary figure S5) to take advantage of the ameliorated photo-thermal resources for higher yields (Tao *et al* 2013, Zhang *et al* 2014a). The cultivars with a longer GP by shortening VGP and lengthening RGP were adopted for early rice to improve yield meanwhile leave more days for transplanting late rice earlier (Wang *et al* 2017a, Ye *et al* 2019). The cultivars with a shorter GP were adopted for late rice to escape the cold stress during heading and grain-filling stages (Zhang *et al* 2016b, Wang *et al* 2016, 2019a). Note that, the cultivars with a longer GP by lengthening both VGP and RGP were adopted for all the three rice types during 2000–2018 except single rice in zone III. The change in VGP could be ascribed to the combined effects of temperature and photoperiod.

We showed that ATDU requirements were positively correlated with \( T_{\text{min}} \) for most rice types and

![Figure 8. Relations of day length (a), (b), (c) and \( T_{\text{min}} \) (d), (e), (f) with ATDU during VGP at all stations for single rice (a), (d), early rice (b), (e) and late rice (c), (f).](image-url)
AEZs (figures 8(d)–(f)). Rice yield has been limited by insufficient photo-thermal resources for decades, especially in southern China. With climate change, increase in solar radiation and temperature advanced transplanting date and delayed heading date, lengthening VGP (increasing ATDU requirements) to make full use of the improved heat resources. Interestingly, a negative correlation between ATDU and temperature was found for late rice in zone VI (figure 8(f)), the warmest zone in southern China. Late rice in low latitudes in China was often damaged by extreme high-temperature events (Zhang et al 2014b, Wang et al 2019b). Temperature, above $T_{\text{opt}}$, contributed only partly even negatively to ATDU according to equation (2). The negative correlation suggested that intensive warming surpassed current cultivars’ photo-thermal requirements and hence threatened rice development in the region and probably exacerbates with climate warming. In addition, day length affected negatively ATDU (figures 8(d)–(f)), suggesting that decreased day length (supplementary figure S4) may decelerate rice development rate, increase ATDU requirements, and thus prolong VGP. The increased RGP can be largely attributed to cultivar turnover (Tao et al 2013, Zhang et al 2014a, Wang et al 2017a, Ye et al 2019). The cultivars with a high ATDU requirement delayed maturity date and consequently lengthened the growth duration (supplementary figure S5). Yet single rice RGP in zone III was strongly decreased because heading date delayed significantly. In the zone, rice heading dates were around 15 July–10 August (DOY 197–223), coinciding with the occurrence of extreme high temperature events caused by subtropical high. Cultivars with a later heading date were adopted by farmers to avoid the heat stress during the heading-flowering stage (Tao et al 2013, Wang et al 2014, Zhang et al 2014a, 2016).

Transplanting is a field management activity, which is directly decided by farmers, but it could be largely influenced by many factors, including local climate, suggestions from agricultural technicians for a specific cultivar and others such as soil physical problems with droughts or water-logging (Waha et al 2013, Ding et al 2020). There was a notion that crop establishment was not affected much more with sowing change by one or two weeks because of increased temperature and good soil-moisture condition (Tao et al 2012, 2014, Zhang et al 2014a, Gao et al 2021).

Our study showed, however, delaying transplanting decreased the length of RGP for late rice by 2 days/decade during 2000–2018, which was comparable with climate impacts and exhibited greater variability (figure 6(f)). Field experiments also proved that adjusting sowing date greatly influenced crop growth and development rate, water use efficiency, source-sink relationship as well as crop resilience to climate (Bonelli et al 2016, Huang et al 2018, Rotili et al 2021). The effects of sowing date shifts therefore should be emphasized as many previous studies did (Tao et al 2014, Zhang et al 2014a, Wang et al 2017a, Ye et al 2019). The impacts of other factors on rice GPs were generally small because fertilization and irrigation were fully applied in China and thus have little effect on the long-term trends of the phenology (Tao et al 2012, 2014, Wang et al 2017a, Ye et al 2019).

4.4. Uncertainties in the study

This study, like many others, also had some uncertainties. First, the regional comparisons could cause some uncertainties due to the uneven distribution of agro-ecological stations. Second, a single temperature threshold over rice development phases might overestimate the contribution of cultivar shifts to rice phenology change. A more detailed model instead of the phenology model used in our study could improve the reliability and robustness of estimations. Third, statistical analysis had inherent uncertainties because the output was affected by sample size and method. Despite the limitations, our study provided an observational evidence for a weakened rice phenological response to climate change using the latest phenological and meteorological observations at a larger number of field stations with a longer period than any previous study on crop phenology (Tao et al 2012, 2014, 2017, Zhang et al 2014a, Abbas et al 2017, Wang et al 2017a, Hu et al 2017, Ye et al 2019). The findings had significant implications for better understanding crop response to climate change and developing effective climate adaptation options.

5. Conclusions

In this study, we used 9393 phenological records at 249 agro-meteorological stations and climate observations at 2400 meteorological stations across China to investigate the spatiotemporal changes of rice phenology during 1981–2018, as well as their relations to temperature change, transplanting date and cultivar shifts. The larger and valuable dataset in both space and time allows us to investigate the response of rice phenology to climate change more critically and reliably. We found rice phenological response to climate warming declined from 1981–1999 to 2000–2018, but climate warming during rice GP did not slow down. Rice GP was generally affected more by $T_{\text{min}}$ than $T_{\text{max}}$ and $T_{\text{mean}}$, for all the rice types. Increased temperature significantly shorten the GP, especially for early rice, followed by single rice and late rice. Cultivar shifts offset totally the effects of climate warming on GP change for all the three rice types. Changes in transplanting date and other agronomic managements had relatively small effect on rice GPs.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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Conflict of interest

The authors declare no competing interests.

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