Projected changes of thermal growing season over Northern Eurasia in a 1.5 °C and 2 °C warming world

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Abstract

Projected changes of the thermal growing season (TGS) over Northern Eurasia at 1.5 °C and 2 °C global warming levels are investigated using 22 CMIP5 models under both RCP4.5 and RCP8.5 scenarios. The multi-model mean projections indicate Northern Eurasia will experience extended and intensified TGSs in a warmer world. The prolongation of TGSs under 1.5 °C and 2 °C warming is attributed to both earlier onset and later termination, with the latter factor playing a dominating role. Interestingly, earlier onset is of greater importance under RCP4.5 than under RCP8.5 in prolonging TGS as the world warms by an additional 0.5 °C. Under both RCPs, growing degree day sum (GDD) above 5 °C is anticipated to increase by 0 °C–450 °C days and 0 °C–650 °C days over Northern Eurasia at 1.5 °C and 2 °C warming, respectively. However, effective GDD (EGDD) which accumulates optimum temperature for the growth of wheat, exhibits a decline in the south of Central Asia under warmer climates. Therefore, for wheat production over Northern Eurasia, adverse effects incurred by scorching temperatures and resultant inadequacy in water availability may counteract benefits from lengthening and warming TGS. In response to a future 1.5 °C and 2 °C warmer world, proper management and scientifically-tailored adaptation are imperative to optimize local-regional agricultural production.

1. Introduction

Northern Eurasia, a vast domain holding 19% of the Earth’s land surface, has undergone a dramatic climatic change in the context of global warming (Groisman et al 2009, Romanovsky et al 2007, IPCC 2013). The surface air temperature (Tas) in this region has exhibited the largest increases around the globe, particularly in the latter half of the 20th century (Groisman et al 2007, Groisman and Soja 2009). Such a drastic warming has inspired growing interests in detecting and projecting changes in temperature-relevant matrix (Fischer et al 2013, Christidis et al 2005), among which indicators pertaining to growing season bear great implications in inferring influences of climate change on both physical and biological systems (Christidis et al 2007, Schwartz et al 2006). Specifically, of vital importance are the changes in timing, temporal span and temperature accumulation of the growing season and their impacts on the phenology shift and vegetation productivity (Piao et al 2007, Linderholm 2006).

The past few decades have witnessed significant changes of thermal growing season (TGS) in the Northern Hemisphere (Peltonen-Sainio et al 2009, Linderholm et al 2008, Menzel et al 2006). Defined as the interval with temperature steadily exceeding certain thresholds, growing season length (GSL) has shown a lengthening trend over much of the Northern Hemisphere (Frich et al 2002, Dong et al 2013, Parmesan and Yohe 2003). Similar significant lengthening in GSL has been validated in many regions by phenological studies, based on field observations and remote sensing data (Menzel and Fabian 1999, Park et al 2016, Yu et al 2018). Moreover, it is reported that the extension of GSL arose jointly from the configuration of an earlier beginning and a delayed ending.
The contributing fractions of the advanced onset and the delayed termination to the prolonged GSL vary across regions. For instance, the prolongation over northern Europe and eastern China could be primarily ascribed to the earlier beginning, while it seems more of a result by later termination in west of China and over mid-high latitudes in North America (Linderholm et al 2008, Dong et al 2013, Zhu et al 2012). In addition, projected changes for these TGS indices are employed in different regions to provide insights about ecological responses to the future warming climate therein. The temperature accumulation during TGS, also referred to as growing degree day sum (GDD), is projected to increase by 2021–2050 of more than 300 °C days in the coastal area of Norway (Engen-Skaugen and Tveito 2004). In Finland, Ruosteenoja et al (2011) reported a 40–50 days prolongation of TGS and a 1.5- to 2-fold GDD compared to the baseline climate under the A2 scenario by the end of the 21st century. They also found widespread lengthening and warming of TGS when they expanded the study region to whole Europe (Ruosteenoja et al 2016).

Parameters of TGS, such as GSL and GDD, are closely linked to agriculture and have been employed as measures for agricultural potential (Richardson et al 2013, Peltonen-Sainio et al 2009). Along with hydrologic and some other effects, TGS have affected and will continue to inflict on crop yields in the coming decades (Lobell and Gourdji 2012, Christiansen et al 2011, Schwartz et al 2006). Assessing the future changes in TGS is critical to aid prognosticate TGS-related agricultural consequences of climate change, particularly for major agricultural production regions (Chen et al 2000, Fischer et al 2005, Cleland et al 2007). This scientific issue appears important in particular and yet under-assessed for Northern Eurasia, where is one of the major global breadbaskets and undergoing dramatic climatic changes (Groisman et al 2007, Kicklighter et al 2014).

Since the Paris Agreement proposed the long-term goal to ‘pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial level’, the aspirational 1.5 °C global warming limit has gained considerable attention from the academic community (Rogelj and Knutti 2016, Schleussner et al 2016, Mitchell et al 2017). The Intergovernmental Panel on Climate Change (IPCC) has accepted the invitation to prepare a special report on global warming of 1.5°C in 2018. Efforts deserve exerting immediately to assess potential impacts of a 1.5°C warming world and associated avoided risks with comparison to a 2°C warming scenario (Mitchell et al 2016). Though regionally differentiated impacts of 1.5°C warming compared to the higher levels have been evaluated in various aspects including weather extremes, monsoon responses, sea level rise and so on, very few of them centered on changing characters of growing season, particularly for Northern Eurasia (Schleussner et al 2015, Lissner and Fischer 2016).

Therefore, the present paper aims to narrow above gaps by quantitatively measuring future changes in TGS-related indices over Northern Eurasia in the context of 1.5 °C and 2 °C rise in global mean temperature and distinguishing their differences. We will further elucidate some particular indications of whether crop production in Northern Eurasia will benefit from TGS changes associated with the 1.5 °C and 2 °C global warming scenarios and the incremental 0.5 °C of warming. Due to impacts and risk related to TGS changes differ according to crop species, we focus on wheat as it is the most widely grown crop in the world (Peltonen-Sainio et al 2009, Lobell et al 2012). In addition, some other major factors that affect wheat production and relevant adaption strategies are also discussed.

2. Data and method

Simulations of surface air temperature from 22 models of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) (listed in table S1 available at stacks.iop.org/ERL/13/035004/mmedia) are employed in this analysis. Projections under three Representative Concentration Pathways (RCP2.6, RCP4.5, RCP8.5) until 2099 are selected. In this context, 17 models are used for the RCP2.6 scenario (marked with asterisks in table S1) and 22 models for RCP4.5 and RCP8.5. High-resolution gridded Climate Research Unit Time Series (CRU TS V4.00, Harris et al 2014) data over 1901–2015 are utilized as observations to compare with model simulations over historical periods. Changes in intensity of hot extremes are assessed using the annual temperature maxima (TXx) defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) for the same CMIP5 multi-model ensemble. Concretely, let TX be the daily maximum temperature, then annual TXs is the maximum value of all the TXs in each year (Fischer et al 2013). All data are regridded to a uniform 1° × 1° grid via bilinear interpolation. Model data are all masked to the gridpoints where CRU data are available as the shadings shown in the upper-left panel in figure 1(a). The wheat harvested areas in Northern Eurasia are retrieved from EarthStat, with detailed information documented in Monfreda et al (2008).

Northern Eurasia is defined as the domain between 15°E–180°E and 40°N–75°N, which is specified in the upper-left quadrant in figure 1(a). The warming magnitude is calculated with respect to the reference period over 1986–2005, which is formally adopted in IPCC assessment reports and favor to eliminate model deviations from observations over the historical period (Schleussner et al 2015, James et al 2017). Given that this reference period has stayed 0.6 °C above pre-industrial levels (IPCC 2013),
Figure 1. (a) Historical and projected annual mean Tas anomalies with respect to 1986–2005 mean under the RCP 2.6 (green), RCP4.5 (blue) and RCP8.5 (red) scenarios for Northern Eurasia and global mean from 22 models (17 models for RCP 2.6) in the CMIP5 multi-model ensemble. Colored solid and dashed lines indicate the projections for Northern Eurasia and Global mean, respectively. Corresponding colored shadings denote the full range of the multi-model ensemble for Northern Eurasia under the three scenarios, respectively. The thin black line and grey shadings denote the multi-model mean and the full range of the historical simulations for Tas anomalies over 1861–2005. The dashed gray lines indicate the baseline (1986–2005), 1.5 °C and 2 °C global warming thresholds relative to the baseline. The thick black line denotes the observed (CRU) Tas anomalies compared to 1986–2005 mean for Northern Eurasia. The vertical black line marks the boundary between historical and RCP simulations. (b) Boxplot of the timings when global annual mean temperature increases cross 1.5 °C and 2 °C thresholds projected by CMIP5 models for RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red). Median and mean projections of the threshold crossing times are indicated by red vertical line and red pentagram, respectively. Black dots including outliers indicate threshold crossing times of all the 22 models (17 models for RCP 2.6) for the three RCPs.

the 1.5 °C and 2 °C limit are equivalent to 0.9 °C and 1.4 °C additional increase above the reference period level, respectively. Following the definition of GSL by ETCCDI, the starting of growing season (GSS) is defined as first span of at least 6 days with daily mean temperature above 5 °C. Similarly, the first span of at least 6 days after 1st July with daily mean temperature below 5 °C indicates the ending of growing season (GSE). Then, GSL is measured by the interval length between GSS and GSE. It should be noted that, if GSS is not found, GSS and GSE will be treated as undefined and GSL will be set to 0. When GSE is not found, GSL will be counted until the end of the calendar year.

Besides, the temperature accumulation of TGS (also referred to as GDD) is calculated by tallying up temperature exceedances above certain thresholds during TGS. Effective GDD (EGDD) is the accumulation of temperature in an optimum interval for crop growth which rule out detrimental extreme temperature. The magnitude of high temperatures that crops can tolerate not only vary by crop species at different development stages, but also, to some extent, by crop variety (Luo 2011, Lobell et al 2012, Gourdji et al 2013). Moreover, heat stress can cause greater harm to wheat during the reproductive phase than during the vegetative phase, due to the direct effect on grain number and dry weight (Wollenweber et al 2003). For winter wheat in
Indian and Australia, temperatures above 34 °C during grain-filling can result in an acceleration of wheat senescence and lower yields (Asseng et al 2011, Lobell et al 2012). For spring wheat, thresholds of high temperature stress during reproductive and grain filling phases used in the thermotolerance analyses were very often in excess of 34 °C (Fokar et al 1998, Gourdji et al 2013). Through extensive review, Farooq et al (2009) identified the maximum temperature limit for wheat growth in the reproductive and grain-filling period is 34.3 °C ± 2.66 °C. For Northern Eurasia, where winter wheat is dominant in the western part and spring wheat clusters in the East, we select the typical 34 °C as the threshold to assess changes of EGDD and its implications for wheat growth during reproductive and grain-filling phases.

3. Results and discussions

3.1. Results
During the historical period, albeit an underestimation of interannual variability of the Tas by multi-model mean, the variability presented by the CMIP5 ensemble encompasses the observed temperature over Northern Eurasia (figure 1(a)). For global mean Tas in figure 1(a), the multi-model mean projections under the lowest emission pathway RCP2.6 yield a temperature increase steadily below the 2 °C limit until the end of this century, consistent with results in IPCC AR5 (IPCC 2013). Higher scenarios like RCP4.5 and RCP8.5, see a much faster increase in global mean temperature. The 2 °C warming target is surpassed by around 2050 and 2040 for RCP4.5 and RCP8.5, respectively. Furthermore, global mean rise of Tas reaches 1.5 °C threshold by around 2030 for all the three scenarios. Comparatively, projected warming over Northern Eurasia is much greater than the global mean in all RCPs. When global mean temperature reaches 1.5 °C and 2 °C warming above pre-industrial levels, larger regional mean temperature rise will occur over Northern Eurasia (figure 1(a)).

To achieve more robust threshold crossing times (TCTs) for global mean warming as reported in Karmalkar and Bradley (2017), time series of global mean temperature are smoothed using 5 year moving mean to calculate TCTs in individual models and each RCP. The scattered dots in figure 1(b) show that, all models except outliers indicate that the 1.5 °C global warming will come true before 2050 for all scenarios. The median TCTs for 1.5 °C threshold all centered around the late 2020s and early 2030s. Regarding the 2 °C warming limit, TCTs under RCP4.5 vary dramatically between models, spanning from the 2030s to the 2070s, whereas TCTs of global warming under RCP8.5 behave more concentrated and are generally a decade in advance compared to counterparts in RCP4.5. Notably, based on the multi-model mean projections marked as red pentagons, the 1.5 °C global warming TCTs of all RCPs range from 2028–2038 and 2 °C global warming will be reached by 2041 and 2053 for RCP8.5 and RCP4.5, respectively. (figure 1(b)). 20 year time slices centered around the multi-model mean TCTs for global mean temperature (with 9 years ahead and 10 years behind) are used to analyze the regional impacts of the 1.5 °C and 2 °C global warming. Because 2 °C global warming is not crossed under RCP2.6 till the end of this century, the following analyses are based on RCP4.5 and RCP8.5.

Changes in various aspects of growing season are calculated as difference between the climatological mean of the 20 year periods characterizing specific warming levels and the reference period. According to the multi-model mean projection under RCP4.5, except for undefined GSSs and GSEs in the far north and northeast part of Northern Eurasia, earlier onset and delayed termination of TGS are both identified at 1.5 °C and 2 °C warming levels (figures 2 (a1)–(a2) and (b1)–(b2)). Quantitatively, at the 1.5 °C warming level, GSSs shift toward earlier by 6–12 days in the southwest corner and by less than 6 days over the other part of Northern Eurasia. Analogously, GSEs delay by 3–6 days in the southeast and by 6–16 d in the northwest. An obviously larger magnitude of the GSS and GSE changes is discerned in the 2 °C warming scenario. As highlighted in the differences between 2 °C and 1.5 °C warming levels (figures a3 and b3), advancement of GSSs reaches about 1–4 d in the central and east and about 4–6 days in the southwest for the 0.5 °C additional warming. Moreover, GSEs will show a further delay of 1–5 days, when the magnitude of global warming amplifies from 1.5 °C–2 °C.

As a consequence of earlier GSS and later GSE, prolongation of GSL occurs at both warming levels for RCP4.5 (figures 2 (c1)–(c2)). The most prominent extension of GSL is found in the western and northern periphery of Northern Eurasia where it attains up to about 12–30 and 20–40 days for 1.5 °C and 2 °C warming, respectively. In other regions over Northern Eurasia, GSL is lengthened by about 3–12 and 6–16 days for 1.5 °C and 2 °C warming, respectively. Accounting for the 0.5 °C difference, the southwest region and the northernmost periphery of Northern Eurasia will experience about 6–16 days longer GSL (figure 2 (c3)). By contrast between magnitude of the GSE delay and the GSS advancement, it can be found that under RCP4.5 delayed termination of TGS makes a primary contribution to the prolongation of GSL at the two warming thresholds compared to the reference period. However, lengthening of GSL induced by the 0.5 °C additional warming is mainly caused by the earlier onset of TGS.

For the higher emission pathway RCP8.5, results concerning the tendency of changes in the GSS, GSE and GSL are generally consistent with that for RCP4.5 (figure 3). The distinction lies in that the magnitude of changes in GSS under RCP8.5 is slightly larger at 1.5 °C warming, but appears to be smaller at 2 °C warming.
in the central of Northern Eurasia than that under RCP4.5. Consequently, in the central area, the differences in GSS between 2 °C and 1.5 °C warming under RCP8.5 appear to be smaller compared to that under RCP4.5 (figures 3(a1)–(a3)). However, in Europe, delay of GSE induced by the 0.5 °C additional warming under RCP8.5 (figures 3(b1)–(b3)) is larger than that under RCP4.5. This mainly attributes to the smaller GSE delay at 1.5 °C warming in Europe under RCP8.5 compared to that under RCP4.5. For GSL changes induced by the 0.5 °C additional warming under RCP8.5, larger extension is found in northern Europe while smaller increase occurs in central Russia when compared to RCP4.5 (figure 3(c3)). Moreover, under RCP8.5, difference in GSE between 2 °C and 1.5 °C warming is slightly larger than that in GSS. Thus, for RCP8.5 delay of GSE contributes a little more to the lengthening of GSL when global mean T as increases from 1.5 °C–2 °C.

Figure 4 illustrates the projected changes in GDD and EGDD with baseline temperature selected as 5 °C at 1.5 °C, 2 °C warming and their differences under RCP4.5 and RCP8.5. Over Northern Eurasia, GDD above 5 °C will also undergo significant increase under both warming scenarios. For both RCPs, the magnitude of the increase ranges from 0 °C–450 °C days and from 0 °C–650 °C days for 1.5 °C and 2 °C, warming, respectively. Measured by absolute changes, the largest increase is projected to occur in the southern periphery of Northern Eurasia under 1.5 °C and 2 °C warming, where higher temperature accumulates during longer TGS. Under the scenario RCP8.5 for a warming of 1.5 °C and 2 °C, projected GDD above 5 °C is relatively smaller than that for RCP4.5 over east Russia and the majority of Europe. Not surprisingly, differences in GDD exist between 2 °C and 1.5 °C warming. The larger differences in GDD between 2 °C and 1.5 °C are identified basically in the same region as that found for
1.5 °C and 2 °C warming under both RCPs. Comparatively, GDD changes induced by the 0.5 °C additional warming are generally smaller under RCP8.5, particularly for the central Russia. In addition, GDD with base temperature selected as 10 °C, as a good indicator for the growth of heat-loving crops, is also investigated. Relative to GDD above 5 °C, increases of GDD above 10 °C appear to be slightly smaller which is 0 °C–400 °C days and 0 °C–550 °C days for 1.5 °C and 2 °C warming, respectively under both RCPs (figure S1). Nevertheless, similar spatial distribution can be found for GDD above 10 °C at both warming levels and their differences.

However, heat resources may become excessive under a warming climate. Extremely high temperatures may be intolerable and may cause detrimental or even lethal effects on wheat (Luo 2011, Lobell et al 2012). To assess impacts of a 1.5 °C and 2 °C warming world on wheat growth over Northern Eurasia in the reproductive and grain-filling phases, exploration is conducted on changes in EGDD calculated as the accumulation of temperature above 5 °C and not exceeding 34 °C. Compared to the increase of GDD above 5 °C at the two warming limits, the magnitude of EGDD enhancement is smaller over the wide region where wheat is grown (denoted by blue hatching in figure 4). This indicates temperature beyond 34 °C is projected to occur in these relatively low-latitudeal areas under warmer climates. Despite increased EGDDs occurring over the majority of Northern Eurasia, decreases of EGDD relative to the reference period are found in the south of Central Asia under both RCPs and both warming levels. And negative changes in EGDD under RCP8.5 are slightly more extensive than that under RCP4.5 at 1.5 °C and 2 °C warming. It is noteworthy that under RCP8.5 coverage of EGDD decreases induced by the 0.5 °C warming increment is even larger compared to those found at the two warming limits relative to the reference period. This implies that some negative impacts induced by a further warming of 0.5 °C may be even larger than those arise in the 1.5 °C and 2 °C warmer worlds relative to the reference period. Therefore, for the south of Central Asia, effective heat resources optimum for wheat growth will get poorer rather than richer in the warmer world. Additional adaptation measures will be needed for the possible amplification of negative effects induced by 0.5 °C additional warming, which will be discussed in the next section. This region may become inappropriate for wheat planting due to decreased production caused by high temperature, although wheat is not grown extensively there.

In the aspect of annual occurrence probability for certain thresholds derived from the reference period, changes in EGDD are further investigated for the 20 year periods corresponding to the considered two warming levels under both RCPs (figure 5, figure S2). When global warming reaches 1.5 °C, the likelihood of EGDD falling below the median of 1986–2005 is below 0.5 over most of the wheat growing region (figure 5(a)). Meanwhile, in the wheat region, the probability of EGDD exceeding 90% percentile of the reference period (10 year return level) is generally larger than 0.1 which is the expected occurrence probability if the climate keeps the same with the reference period (figure 5(b)). This indicates that the wheat growing area will experience increasingly warm TGSs and scarcer cool TGSs at the 1.5 °C warming level. Such changes are more evident for 2 °C warming (figures 5(c) and (d)). For the majority of the wheat area, favoring heat resources for wheat growth will be more frequent for both warming levels. However, it deserves

Figure 4. Projected multi-model mean changes in growing degree days (GDD) ((a1)–(a3) for RCP4.5, (b1)–(b3) for RCP8.5) and effective growing degree days (EGDD) ((c1)–(c3) for RCP4.5, (d1)–(d3) for RCP8.5) of TGS at 1.5 °C global warming (left panels), 2.0 °C global warming (middle panels), and their differences (right panels). The unit is °C days and base temperature is 5 °C. Blue hatching denotes the area where wheat is grown.
to be noted that in the south of Central Asia, opposite condition is found that cool TGs rather than warm TGs will occur in this area more frequently. This confirms the above-mentioned negative absolute changes for climatological mean EGDD in this region under 1.5°C and 2°C global warming. From the average probabilities of EGDD over wheat producing area, it is also clearly seen that the occurrence probabilities of high EGDD are far beyond low EGDD for different return levels in the wheat growing area (figures 5(e) and (f)).

3.2. Discussions

In a warmer world, the prolongation of TGs and increase of physiologically effective heat resources are projected to occur across Northern Eurasia, which will provide beneficial conditions for the growth of crops. Nonetheless, an extension of TGs in autumn is less effective for plant photosynthesis because of the low light, reduced solar radiation and short days in autumn (Peltonen-Sainio et al. 2009, Ruosteenoja and Räisänen 2013). Provided that water and light are sufficient, GSL longer than 250 or 300 d potentially allows double-cropping (Grass et al. 2013). Under both RCPs, GSL beyond 250 d rises from about 13%–16% and 18% for 1.5°C and 2°C warming, respectively, in the wheat producing area over Northern Eurasia (figure S3). Furthermore, lengthening of TGs allows potential cultivation land for agriculture in high latitudes (Schierhorn et al. 2013, 2014a), whereas occasional cold TGs induced by inter-annual variations of TG parameters will keep farmer prudent to expand cultivation area (Fronzek and Carter 2007). Thus, TGs changes induced by global temperature rise are generally favorable for the increase of yield potential over Northern Eurasia. However, in consideration of some negative effects induced by climate change and yield gaps, future changes in crop production is still unclear (Schierhorn et al. 2014b, Porter et al. 2014). More frequent temperature extremes in the future and favorable conditions for pests and pathogens may restrain the growth of crops (Patterson et al. 1999, IPCC 2013, Fischer et al. 2013). For wheat, if the harmful high temperature is ruled out for temperature sums, decreases of EGDD which means possible insufficient heat resources will occur in the south of Central Asia area at both warming levels. In addition, under RCP4.5, land fraction of TXx >37°C (beyond 37°C wheat growth stops, Porter and Gawith 1999) in the wheat growing area over Northern Eurasia increases from 30.3%–41.6% and 45.8% for 1.5°C and 2°C warming, respectively, (figure 6(a)). And it is possible for all wheat growing area in Northern Eurasia to suffer from TXx beyond 37°C under 1.5°C warming and the possibility will rise further at 2°C warming (figures 6 and S4). Besides temperature-related factors, the confounding effects of other major factors must be accounted for quantification of the impact of future climatic changes on wheat production over Northern Eurasia. Among the major factors that affect
crop growth, one important and unneglectable factor is the condition of water resources (Piao et al. 2010, Sheffield et al. 2012, Lobell and Gourdji 2012). For Northern Eurasia, water deficit is the strongest controlling factor for the wheat harvest over the major wheat producing areas (Groisman and Soja 2009, Schierhorn et al. 2014b). Enhanced evapotranspiration under a warming climate may intensify agricultural droughts and decimate water supply required for the wheat growth over Northern Eurasia, particularly for regions already suffering from water scarcity (Huntington 2006, Liu et al. 2014). Due to complications to estimate global trends in evapotranspiration and uncertainties in precipitation projections, future changes of surface water budget over Northern Eurasia remain uncertain (Ohmura and Wild 2002, IPCC 2013, Liu et al. 2014). Therefore, uncertainties still exist in future climate conditions over Northern Eurasia and some adverse impacts may counteract the positive effects brought by the longer and warmer TGS. These facets are likely to increase risk and uncertainty of wheat production in this region under a warming climate.

To mitigate the strike of high temperatures and extremes, shifting growing period allowed by the earlier onset of TGS is one important measure (Mueller et al. 2015). Anther effective way is to transfer farmland to the more arable area in high latitudes (Schierhorn et al. 2013, 2014a). Strengthening the development of sound irrigation systems and the water resource management and introducing varieties tolerant of excessive heat and drought can also offset the negative effects (Peltonen-Sainio et al. 2009, Schierhorn et al. 2014b). Considering spatial and temporal variations of TGS and different responses of various crops to climate change, proper management and scientifically tailored adaption measures are needed for local and regional agricultural production, which is worth more profound exploration.

4. Concluding remarks

Based on CMIP5 multi-model ensemble, projected changes of thermal growing season and relevant implications for wheat production over Northern Eurasia at 1.5 °C and 2 °C global warming and their differences are investigated under RCP4.5 and RCP8.5 scenarios. Under both RCPs, TGS over Northern Eurasia under both warming levels will experience prolongation and intensification, with their magnitude noticeably larger in the 2 °C warmer world. The prolonged TGSs are attributed to both the earlier onset and later termination of TGSs, with the latter account for the main part. Heat resources measured as GDD above 10 °C and 650 °C additional warming is even amplified compared to those detected under 1.5 °C and 2 °C warming relative to the reference period. In a warmer world, accompanying negative effects from temperature extremes and limited water availability may offset the positive impacts brought by the prolonged and warmer TGS, which is likely to increase the uncertainty of future wheat production over Northern Eurasia. In response to future impacts of climate change, proper management and scientifically tailored adaptation measures need to be formulated for local and regional agricultural production.

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