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Changing Lengths of the Four Seasons by Global Warming

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Key Points:

- Climate change has driven longer and hotter summers, shorter and warmer winters, shorter springs and autumns
- The onsets of spring and summer are advanced, while the onsets of autumn and winter are delayed
- Such changes in four seasons can be mainly attributed to greenhouse-warming, and will be amplified under the business-as-usual scenario

Supporting Information:

- Supporting Information S1
- Movie S1

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Abstract

How long will the four seasons be by 2100? Increasing evidence suggests that the length of a single season or in regional scales has changed under global warming, but a hemispherical-scale response of the four seasons in the past and future remains unknown. We find that summer in the Northern Hemisphere midlatitudes has lengthened, whereas winter has shortened, owing to shifts in their onsets and withdrawals, accompanied by shorter spring and autumn. Such changes in lengths and onsets can be mainly attributed to greenhouse-warming. Even if the current warming rate does not accelerate, changes in seasons will still be exacerbated in the future. Under the business-as-usual scenario, summer is projected to last nearly half a year, but winter less than 2 months by 2100. The changing seasonal clock signifies disturbed agriculture seasons and rhythm of species activities, more frequent heat waves, storms and wildfires, amounting to increased risks to humanity.

Plain Language Summary

A series of phenomena such as early flowering of plants and early migratory birds are suggesting that the traditional four seasons may have changed. We focus on how the four seasons changed during 1952–2011 and will change by the end of this century in the warming Northern Hemisphere midlatitudes. We find that lengths and start dates of the four seasons have changed, and the changes will be amplified in the future. Over the period of 1952–2011, the length of summer increased from 78 to 95 days and that of spring, autumn and winter decreased from 124 to 115, 87 to 82, and 76 to 73 days, respectively. In addition, summer is projected to last nearly half a year, but winter less than 2 months by 2100. Such changes can trigger a chain of reactions in agriculture, policy-making for agricultural management and disaster prevention requires adjustment accordingly. The seasonal-related topics involving ecology, the ocean and the atmosphere also need to be revisited.

1. Introduction

As global mean temperature rises, climate-related impacts and risks are increasing rapidly (Hoegh-Guldberg et al., 2019). One prominent example is that global warming has caused the phase and temperature amplitude of seasons to shift significantly, which have been detected in both temperature (Christidis et al., 2007; Menzel & Fabian, 1999; Park et al., 2018; Peña-Ortiz et al., 2015; Santer et al., 2018; Yan et al., 2011) and phenological indicators (Allstadt et al., 2015; Schwartz et al., 2006). The changes in phase of the four seasons include the expansion and contraction of lengths and the drift of onsets (Stine et al., 2009). Therefore, seasonal cycles of the Earth's climate at temperate latitudes are no longer appropriately defined by dividing the year into four equal-length seasons (Trenberth, 1983). Many signals in ecological and physical systems have been subjected to seasonal changes. The most obvious are related to rhythms of living things; for instance, traditional phenological cycles of plants (Buermann et al., 2018; Reyes-Fox et al., 2014; Steltzer & Post, 2009) and bird migration patterns have shifted in response to seasonal changes (Both et al., 2006;

Horton et al., 2020). Temporal and spatial mismatches among organisms are also gradually exaggerating because not all species cope with seasonal changes at the same rate or in the same direction (Samplonius & Both, 2019), which disrupts the structure and function of ecological communities. Even more serious is that seasonal changes can magnify the strain on humans imposed by global warming. People are exposed to more allergenic pollen and longer allergic periods owing to ongoing extension of the growing season (Anenberg et al., 2017). In addition, tropical mosquitoes carrying viruses are likely to expand northward and bring about explosive outbreaks during longer and hotter summers, especially when introduced into regions without previous occurrence (Ryan et al., 2019). These impacts caused by variations in seasons heighten the urgency of understanding how the phase and temperature of seasons change and whether they will continue in the future (Paniw et al., 2019).

While previous studies have quantified observed variations in length of a single season or in regional scales (Christidis et al., 2007; Park et al., 2018; Peña-Ortiz et al., 2015; Yan et al., 2011), a hemispherical-scale response of the four seasons is lacking. Here, we consider how the four seasons changed during 1952–2011 and will change by the end of this century in the warming Northern Hemisphere midlatitudes (30–60°N), where the division of the four seasons based on temperature is readily available. At low latitudes (0–30°N), the air temperatures vary so little throughout the year that the differences in temperature among the four seasons are not obvious (Santer et al., 2018). Tropical seasons are generally divided into wet seasons and dry seasons according to precipitation. Consequently, based on temperature, division of the year into four seasons at low latitudes is not appropriate, so are high latitudes (60–90°N), where the winter is long and cold, and the summer is short and warm (Trenberth, 1983).

2. Data and Methods

2.1. Data

Temperature data in this study were obtained from observations and multimodel ensemble simulations. The observed data were obtained from the Hadley Centre's Global Historical Climatology Network Daily (HadGHCND) and include gridded data of daily maximum and minimum temperatures over land with a horizontal resolution of 3.75° longitude × 2.5° latitude (Caesar et al., 2006). Daily mean observed temperature for the period 1951–2011 was calculated as the average of the maximum and minimum. The multimodel ensemble simulations for the period 1951–2100 were obtained from the Coupled Model Intercomparison Project 5 (CMIP5) and 6 (CMIP6). For CMIP5, two different representative concentration pathways (RCPs) were selected. RCP4.5 is a stabilization scenario, with the total radiative forcing rising until 2070 followed by stable concentrations (without an overshoot pathway) to 4.5 W m^{-2} after 2070 (Thomson et al., 2011). RCP8.5 is a continuously rising radiative forcing pathway in which the radiative forcing level by the end of the 21st century will be approximately 8.5 W m^{-2} (Riahi et al., 2011). SSP2-4.5 and SSP5-8.5 were selected for CMIP6. For SSPx-y, SSP represents shared socioeconomic pathways, and *x* and *y* represent the specific SSP and the forcing pathway, respectively. Specifically, SSP2-4.5 represents the middle of the future forcing pathway range, and SSP5-8.5 represents the high end of the future forcing pathway range. SSP2-4.5 and SSP5-8.5 update the RCP4.5 and RCP8.5 pathways, respectively (Gidden et al., 2019; O'Neill et al., 2016). Twenty-one global climate models from CMIP5 and 16 from CMIP6 were considered in our study (Figure S1) and include both historical climate simulations (1951–2011) and climate projections (2015–2100). Note that the historical climate simulations (1951–2011) of CMIP5 were constructed by merging historical experiments (1951–2005) with future projections based on the RCP4.5 scenario (2006–2011).

2.2. Definition of the Four Seasons

For convenience of analysis, the temperatures on February 29 of leap years were excluded to restrict each year to 365 days, which had no effect on the calculation of long-term trends. To redivide the four seasons, we defined local temperature thresholds following previous methods (Christidis et al., 2007; Park et al., 2018) as outlined below. Summer started when the temperature exceeded the 75th percentile of temperature averaged over 1952–2011 and ended when the temperature was below the 75th percentile. The temperature threshold for winter was defined as the 25th percentile. Spring was regarded as the transition from winter to summer with increasing temperature, and autumn was defined as the transition from summer to winter

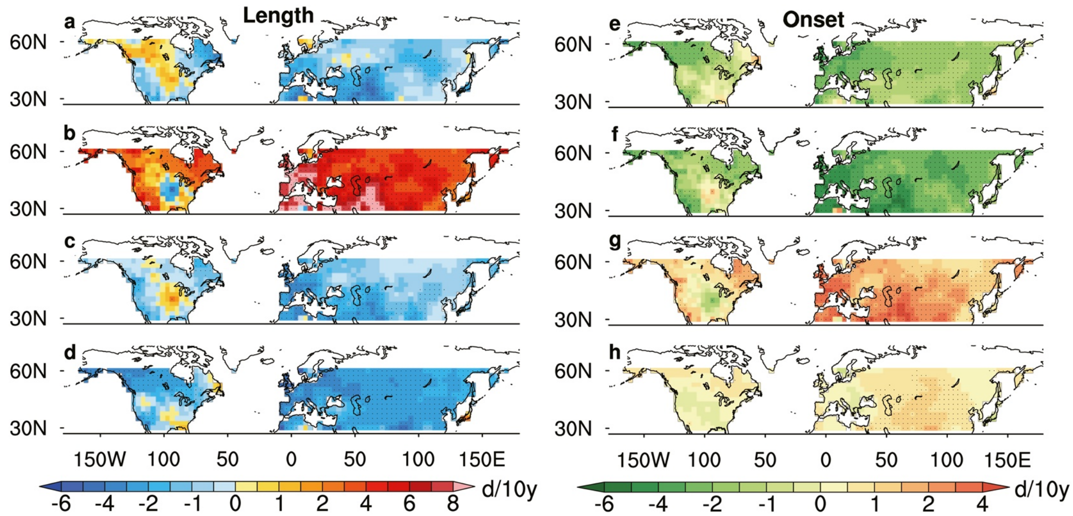

Figure 1. Spatial distributions of the linear trends in season lengths and onsets during the period of 1952–2011. Seasonal distributions of spring (a and e), summer (b and f), autumn (c and g), and winter (d and h). A negative (positive) onset means an advance (delay) in seasonal start. Dotted grids indicate statistically significant trends at the 5% level based on Student's *t*-test.

with decreasing temperature. A third-degree polynomial fitted to the raw observed data was employed to smooth day-to-day temperature fluctuations to avoid more than two intersections between each temperature threshold and observed daily temperature (Christidis et al., 2007; Park et al., 2018) (Figure S2). The temperature thresholds varying from regions to regions well reflect the response of the four seasons to swift climate change and the differences in the four seasons among different regions. Values related to seasonal variations from both observations and model data were computed with the same thresholds.

3. Results

3.1. Observed Changes in Seasonal Cycles

To provide a comprehensive explanation of variations in the four seasons under climate warming, we first calculated the changed linear trends in lengths from 1952 to 2011 in the Northern Hemisphere midlatitudes. For the observed, we found that the hemispheric-scaled summer expanded, spring, autumn and winter contracted (Figures 1a–1c and 1d). The trends of the four seasons in some areas of North America were contrary to the overall trends (Figures 1a–1c and 1d), which is likely attributed to the strong influence of internal climate variability (Huang et al., 2017). In the study area, the most prominent changes in seasonal durations were in the direction of longer summers and shorter winters. From 1952 to 2011, summer length extended at an average rate of 4.2 days every 10 years (d/10 years), while winter length shortened at an average rate of 2.1 d/10 years (Table S1). The durations of spring and autumn changed slightly, shrinking at rates of 1.0 and 1.1 d/10 years, respectively (Table S1). The most obvious area of changes in lengths of the four seasons is near the Mediterranean region, which is consistent with the strengthening seasonality around the Mediterranean region since 1950s in the context that seasonality is weakening in Northern Hemispheric mid-high latitudes (Qian & Zhang, 2019). The Tibet Plateau and its western regions also show greater changes.

As the lengths of the four seasons changed, so did the onsets of the four seasons (Figures 1e–1g and 1h). Spring and summer started earlier by 1.6 days/10 years and 2.5 days/10 years, respectively, while the onset of autumn and winter was delayed by 1.7 days/10 years and 0.5 days/10 years, respectively (Table S2). The changes in onsets showed apparent regional differences. The onsets of spring, summer and autumn in western Eurasia exhibited the strongest trends (Figures 1e–1g), and the delay of the start of winter was the most pronounced on the Qinghai Tibetan Plateau (Figure 1h), which is consistent with the spatial distribution of the four seasons lengths. Therefore, the variations in lengths of the four seasons are the outcomes of the displacement of seasonal onsets. The accurate onsets of the four seasons are more instructive to the cyclical

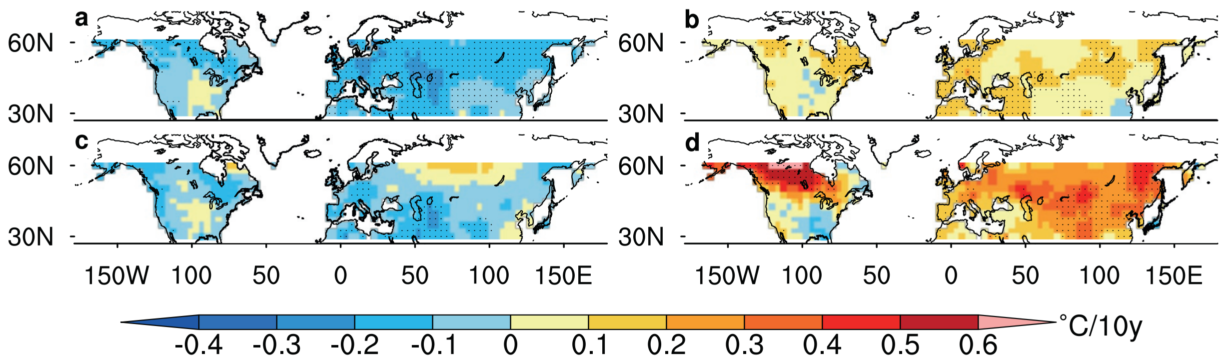

Figure 2. The Spatial distributions of the linear trends in temperatures within the lengths of four seasons over 1952–2011. Seasonal distributions of spring (a and e), summer (b and f), autumn (c and g), and winter (d and h). Dotted grids indicate statistically significant trends at the 5% level based on Student's *t*-test.

events of animal and plant phenology. For example, breeding birds need select a breeding window to feed their offspring with adequate food and avoid enemies. However, due to the early spring, breeding birds breed early and the breeding window is becoming narrower, which commit them to severe food shortages and threats from predators (Descamps et al., 2019).

Variations in both seasonal phases and seasonal temperatures have been detected under the temperature threshold definition. Temperature has risen clearly in extended summers and shortened winters from 1952 to 2011 (Figures 2b and 2d). In summer, the temperature increased at the rate of 0.089°C per 10 years (°C/10 years) (Table S3). Since the temperature threshold that define each season are certain, the temperature variation in summer is consistent with the fact that extreme high-temperature events have occurred more frequently in summers (Sheridan & Lee, 2018). In the extended summer season, from May to September in the Northern Hemisphere, the frequency, duration and cumulative heat of heatwave have significantly increased since 1950s (Perkins-Kirkpatrick & Lewis, 2020). Hotter and longer summers seriously disrupt energy productivity and utilization (Orlov et al., 2020), such as increasing the energy demand for cooling and affecting hydropower generation. The summers also plague vegetation and forests, higher large-wildfire frequency and longer wildfire seasons during heatwaves (Westerling et al., 2006). In addition, existing evidence suggests that high temperature is even tied to human physical and mental health. Groups who work outdoors or indoors without cooling systems are facing severe heat exhaustion (Kjellstrom, 2015). The same is true for mental health: the higher the temperature, the higher the prevalence of mental health (Obradovich et al., 2018).

In winter, the temperature increased at the rate of 0.260°C/10 years (Table S3). The temperatures in the whole Eastern Hemisphere have changed by more than 0.2°C/10 years, especially in eastern East Asia. The warming trend of winter was most pronounced in northern North America, where the temperature rose at the rate of more than 0.4°C/10 years (Figure 2d). Warmer winters have a great impact on crop yields. The insufficient chilling demand for bud dormancy due to milder winters stunt the growth of plants, resulting in reduced yields and quality (Bartolini et al., 2019; Fu et al., 2015). In addition, milder and shorter winters come with great challenges visible in public security. Higher temperatures and shorter winter periods cause higher crime rates across several regions of the United States (Harp & Karnauskas, 2018). Tourism also has also faced the pressure from winter changes. Highly snow-dependent ski areas are most easily and directly affected by winter (Beniston, 2003).

However, the temperature in spring decreased at the 95% confidence level (Figure 2b). Increasingly colder and earlier spring seasons may pose a greater risk of false spring (subsequent hard freezes damage plants that awaken prematurely from dormancy) for plants (Allstadt et al., 2015), which may inflict a heavy blow to the economy (Kral-O'Brien et al., 2019). The false spring in Michigan in 2012 resulted in more than half a billion dollars loss from local fruit trees (Knudson, 2012). Plants that survive false springs may not be able to grow successfully due to weak resistance to future stress (Allstadt et al., 2015). The seasonal effect is not limited to acting on itself; it spreads to other seasons and even brings about long-term consequences; for instance, early springs are likely to indicate early summers (Crimmins & Crimmins, 2019), early growth

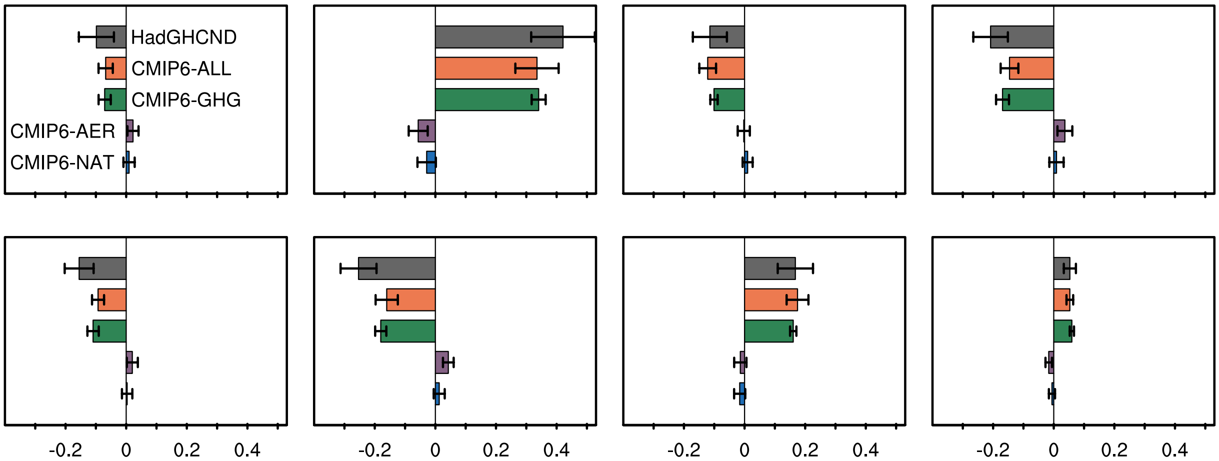

Figure 3. Temporal trends for onsets and lengths of the four seasons over the 1952–2011 period from observations of HadGHCND and different experiments of CMIP6. Seasonal trends in lengths (a–d) and onsets (e–h) of spring (a and e), summer (b and f), autumn (c and g), and winter (d and h). CMIP6-ALL represents all forcing simulation, CMIP6-GHG represents well-mixed greenhouse gases run, CMIP6-AER represents anthropogenic aerosols forcing run and CMIP6-NAT represents natural forcing run. The uncertainty is calculated as double standard errors, which reflects the 95% confidence interval. HadGHCND, Hadley Centre's Global Historical Climatology Network Daily; CMIP6, Coupled Model Intercomparison Project 6.

due to advanced onset of spring may face a shortage of water in the remainder of the growing season (Buermann et al., 2018), and short and warm winters can exacerbate the occurrence of false springs (Allstadt et al., 2015). The chain reactions complicate the effects of seasonal changes. Robust seasonal forecasts will enable the optimization of the operation and management of activities, such as agricultural production, and avoid some possible risks.

To find the contributions of different factors including greenhouse gases, anthropogenic aerosols, and natural forcing to the observed trends in lengths and onsets of the four seasons, we compared multimodel mean trends of the lengths and onsets of the four seasons with the observations (Table S4 and Figure 3). The trends from all forcing simulation show similar trend to the observations, and the trends forced by only well-mixed greenhouse gases are similar to all forcing simulation. However, the simulations ran by only anthropogenic aerosols forcing or only natural forcing produce weak or even contrary trends. The results suggest that greenhouse gases forcing dominate changes in lengths and onsets of the four seasons. The changes in lengths and onsets of the four seasons are also calculated based on detrended observational data (Figure S3). After removing warming trends, the changes in seasonal cycles are greatly weakened, which also indicate that greenhouse-warming trends induced variations in the four seasons.

3.2. Projected Changes in Seasonal Cycles

Previous studies have not assessed future changes in the four seasons of the midlatitude Northern Hemisphere, as such, whether these changes continue is an important issue. We use the same definition of seasonal cycle as in the observed to project changes in seasonal cycles in the future. We first evaluated CMIP5 and CMIP6 models using the Taylor diagram analysis, and selected 21 CMIP5 models and 16 CMIP6 models whose historical experiments all reproduced the temperature climatology well (Figure S1). Both CMIP5 and CMIP6 ensemble simulations from historical experiments also reproduced the changed seasonal trend direction well (Figure 4, Tables S1–S3, and Figures S4–S6). Based on the multimodel ensemble 2-m surface air temperature from CMIP5 and CMIP6, the changed trends of the four seasons are expected to amplify in the future. Under the stabilization scenario (RCP4.5 and SSP2-4.5), trends in length and onset from 2016 to 2100 are close to the observed extrapolation (the trends in length and onset of the four seasons during 2016–2100 are the same as observed trends from HadGHCND during 1952–2011) (Figure 4 and Figures S7–S8), indicating that even if seasons are to continue at the current rate observed, a longer summer and shorter winter will become the new normal in the 21st century.

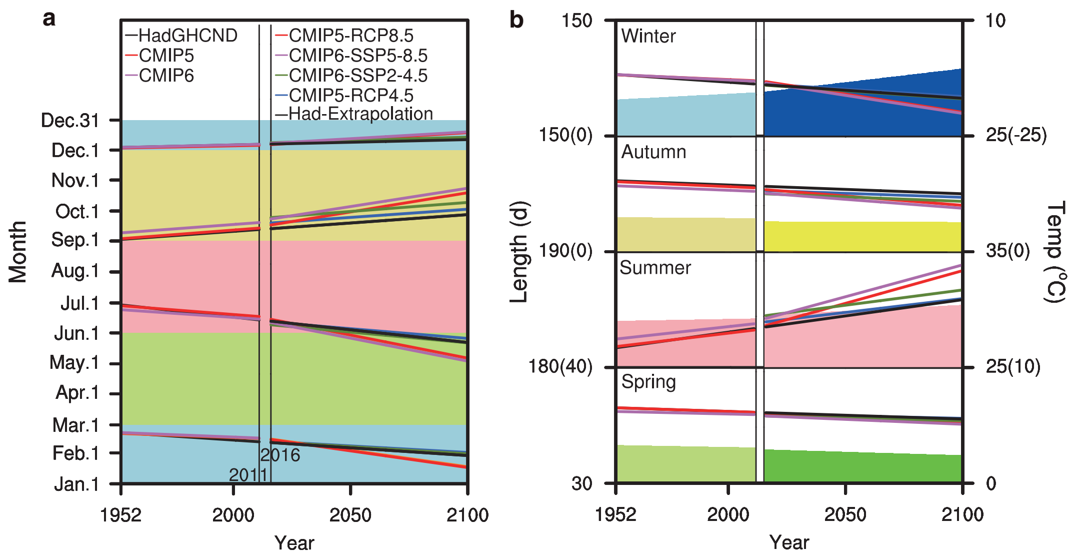

Figure 4. Temporal trends for onsets, lengths and temperatures of the four seasons during the period of 1952–2011 (historical) and 2016–2100 (future). (a) Onsets are shown in (a). The shading denotes the range of traditional seasons (green: spring, pink: summer, khaki: autumn, blue: winter). (b) Lengths and temperatures are shown in (b) The curve is the length trend, and shading is the temperature trend from HadGHCND and RCP8.5 (trends for others are listed in Table S3). The labels on the *Y* axis in parentheses indicate coordinates of the graph above, and labels outside the parentheses indicate the coordinates below. HadGHCND, Hadley Centre's Global Historical Climatology Network Daily; RCP, representative concentration pathways.

With radiative forcing levels rising, spring and summer will start earlier, with respective mean rates of 3.3 days/10 years and 4.6 days/10 years under RCP8.5, while autumn and winter will start later, by 3.8 days/10 years and 1.4 days/10 years, consistent with the variations under SSP5-8.5 (Tables S1–S2, Figures S10–S11). The shifts in onsets of the four seasons will cause the length of spring, autumn and winter to shrink at a rate of 1.3, 2.4, 4.7 days/10 years and summer to extend at 8.5 days/10 years (Table S1). Except for spring, the length of the other three seasons under RCP8.5 is more than twice as long as the observed. As a result, there is good potential for a 166-days summer and 31-days winter in 2100 (Figure 5 and Table S5). The most aggressive scenario alarms us that we will be on a dangerous path of agriculture, ecology, and human health for climate change if emissions are not curbed (Christidis et al., 2020; Power & Delage, 2019). People will also face a higher risk of seasonal temperature in the future (Figures S9 and S12), especially in summer and winter, when the temperature trend will be nearly three times that during the period of 1952–2011 under the scenario of RCP8.5 and SSP5-8.5 (Figures 4b and Table S3). The changes may magnify the impact of the four seasons, and even cause more severe consequences. Seasonal change is a global phenomenon; however, the magnitudes are not uniform across spatial scales, and specific regional research is necessary in the future.

To examine sensitivity to definition of seasons, the possible influence of temperature thresholds based on climatology from different periods and defined by different percentiles has been noticed. We have calculated variations in lengths, onsets and temperatures of the four seasons under different definitions whose temperature thresholds defined by temperature averaged over different periods, such as 1952–2011, 1970–1999, 1952–1981, and 1982–2011 (Figures S13–S18 and Tables S6–S8). The results are insensitive to reasonable definitions. Similar results are also observed when temperature thresholds are defined by different percentiles (25th/75th, 25th/65th, 25th/70th, 25th/80th, 20th/75th, 30th/75th, 35th/75th). Therefore, the results are robust to temperature thresholds based on climatology from different periods and defined by different percentiles.

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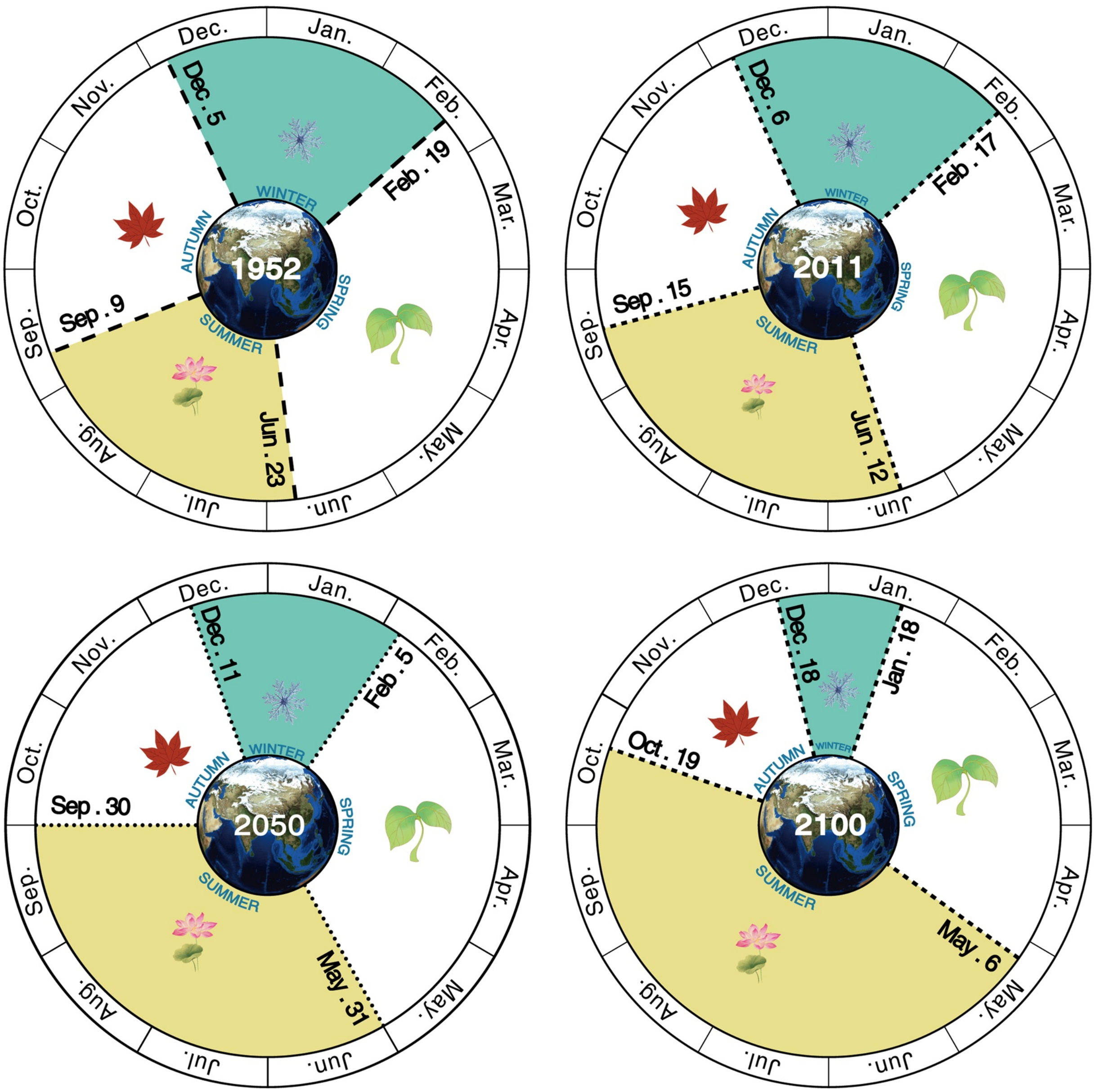

Figure 5. Onsets and lengths of the four seasons in 1952, 2011, 2050, and 2100. The top row is from HadGHCND, and the bottom row is from RCP8.5. HadGHCND, Hadley Centre's Global Historical Climatology Network Daily; RCP, representative concentration pathways.

4. Conclusions

As global warming intensifies, the four seasons of a year no longer have equal months, and their onsets are irregular. Over the period of 1952–2011, the length of summer in the Northern Hemisphere midlatitude increased from 78 to 95 days and that of spring, autumn and winter decreased from 124 to 115, 87 to 82 and 76 to 73 days, respectively (Table S5). Accordingly, seasonal temperature also changed, with summer and winter becoming warmer. Longer and hotter summers, shorter and warmer winters, shorter spring and autumn seasons are the new normal, and this kind of trend may be unavoidably amplified in the future due to the rising radiative forcing. Variations of the four seasons simulation from CMIP5 and CMIP6 under different scenarios exhibit a range of plausible future four seasons, providing decision-makers with a broader basis for decision-making. Under the business-as-usual scenario, spring and summer will start about a month earlier than 2011 by the end of the century, autumn and winter start about half a month later, which result in nearly half a year of summer and less than 2 months of winter in 2100. As lengths of the four seasons change continue, which can trigger a chain of reactions, policy-making for agricultural management, health care, and disaster prevention requires adjustment. Above all, seasonal-related topics involving ecology, the ocean and the atmosphere need to be revisited because seasons are the basic time parameter for a wide range of natural phenomena (Cassou & Cattiaux, 2016).

Data Availability Statement

The HadGHCND data are available for download (https://www.metoffice.gov.uk/hadobs/hadghcnd/download.html). The CMIP5 and CMIP6 outputs are downloaded from (https://esgf-node.llnl.gov/search/cmip5/; https://esgf-node.llnl.gov/search/cmip6/).

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