LETTER

Lengthening of summer season over the Northern Hemisphere under 1.5 °C and 2.0 °C global warming

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Keywords: summer season length, global warming, Paris Agreement, seasonal cycle

Abstract
Summer season has lengthened substantially across Northern Hemisphere (NH) land over the past decades, which has been attributed to anthropogenic greenhouse gas increases. This study examines additional future changes in summer season onset and withdrawal under 1.5 °C and 2.0 °C global warming conditions using multiple atmospheric global climate model (AGCM) large-ensemble simulations from the Half a degree Additional warming, Prognosis and Projected Impacts project. Five AGCMs provide more than 100 runs of 10 year length for three experiments: All-Hist (current decade: 2006–2015), Plus15, and Plus20 (1.5 °C and 2.0 °C above pre-industrial condition, respectively). Results show that with 1.5 °C and 2.0 °C warmer conditions summer season will become longer by a few days to weeks over entire NH extratropical lands, with slightly larger contributions by delay in withdrawal due to stronger warming in late summer. Stronger changes are observed more in lower latitudes than higher latitudes and largest expansion (up to three weeks) is found over East Asia and the Mediterranean. Associated changes in summer-like day frequency is further analyzed focusing on the extended summer edges. The hot days occur more frequently in lower latitudes including East Asia, USA and Mediterranean, in accord with largest summer season lengthening. Further, difference between Plus15 and Plus20 experiments indicates that summer season lengthening and associated increases in hot days can be reduced significantly if warming is limited to 1.5 °C. Overall, similar results are obtained from Coupled Model Intercomparison Project phase 5 coupled GCM simulations (based on RCP8.5 scenario experiments), suggesting a weak influence of air-sea coupling on summer season timing changes.

1. Introduction

Identifying changes in seasonal cycle is important due to its direct impact on human society and environment like agriculture, industries, water resources, and biodiversity. For this reason, various methods were employed to figure out the changes in seasonal cycle of daily temperatures (Mann and Park 1996, Wallace and Osborn 2002, Stine et al 2009, Dwyer et al 2012, Qian and Zhang 2015, Cornes et al 2017). In addition to simple investigation of the changes in seasonal mean or extreme temperatures, changes in amplitude and phase of seasonal cycle have been analyzed. For the amplitude of seasonal cycle, Qian and Zhang (2015) identified the dominant impact of human-induced anthropogenic forcing over the Northern Hemisphere (NH) land areas such that model simulations including greenhouse gas increases can reproduce well the observed weakening of seasonal cycle. A greater warming in winter than in summer pattern over the northern high latitudes is consistent with future projections forced with increasing greenhouse gases (e.g. Dwyer et al 2012, Yetella and England 2018). Regarding the phase of seasonal cycle, while observations show a trend of phase advance, i.e. earlier minimum and
maximum annual temperature during the past decades, models consistently simulate the delayed timing of seasonal cycle (Mann and Park 1996, Wallace and Osborn 2002, Dwyer et al 2012, Yettelia and England 2018). Stine and Huybers (2012) and Cornes et al (2017) found that the observed earlier phasing at hemispheric scale was largely due to the influences of internal climate variability, particularly, the Northern Annular Mode.

The length and/or timing of growing season or specific seasons is another good metric to monitor the ongoing and future changes in seasonal cycle. Several studies have investigated the direct change of summer season length, usually defined as the hottest period in a year from regional to global scales. In particular, relative temperature thresholds were applied to define summer season over each region, which enables one to combine different regions and assess large-scale changes. Such studies consistently found prolonged summer season with advanced start and delayed termination of summer over Europe (Peña-Ortiz et al 2015, Ruosteenoja et al 2019), United States (Allen and Sheridan 2016), China (Dong et al 2010), NH (Park et al 2018) and Southern Hemisphere (Weller et al 2020). By comparing the observed and model simulated patterns under different external forcings, Park et al (2018) and Weller et al (2020) found that human-induced anthropogenic forcing is the major contributor to the observed lengthening of summer season in both hemispheres.

Since the Paris Agreement 2015 committed to make an effort to holding the global average temperature rise to 1.5 °C rather than 2.0 °C based on pre-industrial (1861–1880) conditions, quantifying differences between two warming scenarios has become important to motivate the socioeconomic effort to sustain below 2.0 °C warming (Hulme 2016). Significant increases in extreme heat events by additional half degree of warming were reported over many regions including Australia, Europe, East Asia, and South Asia (e.g. King and Karoly 2017, King et al 2017, Mishra et al 2017, Dosio et al 2018, Lee and Min 2018), which indicate corresponding potential benefits of global warming mitigation. However, few studies analyzed future changes in seasonal cycles at the global warming mitigation targets. Extreme heat events will be more frequent and more intense and persist longer under stronger warming (Pfleiderer et al 2019), but the contribution of summer season lengthening to the increasing heat events has not been quantified.

This study aims at examining how the summer would expand over the NH land regions in the future under 1.5 °C and 2.0 °C global warming conditions using the multiple atmospheric global climate model (AGCM) large-ensemble simulations which were performed by the Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI, Mitchell et al 2017). Because the lengthened summer season will provide favorable conditions for extreme heat waves, regional changes in summer-like days during the extended onset and withdrawal days are also analyzed. Results from coupled model simulations based on Coupled Model Intercomparison Project phase 5 (CMIP5) transient emission scenarios are compared to assess robustness of the seasonal cycle changes to the model samples.

This paper is structured as follows. Section 2 describes model simulation and reanalysis data and explains the analysis method. In section 3, future changes in summer season timing and summer-like day frequencies are analyzed for HAPPI simulations in comparison with CMIP5-based results, considering the entire NH, mid- and high-latitude, and six sub-continental regions. Summary and conclusions are provided in section 4.

2. Data and methods

2.1. HAPPI and CMIP5 simulations

AGCM large-ensemble simulations provided by the HAPPI project (Mitchell et al 2017) are analyzed, which were performed to estimate climate changes under 1.5 °C and 2.0 °C warmer conditions relative to the pre-industrial condition (1861–1880). Five AGCMs provide more than 100 runs of 10 year length for three experiments (table 1): All-Hist (current decade: 2006–2015), Plus15, and Plus20 (1.5 °C and 2.0 °C above pre-industrial condition, respectively). The observed sea surface temperature and sea-ice boundary conditions were prescribed for the All-Hist runs while those for Plus15 and Plus20 were estimated based on multi-model means of RCP2.6 and RCP4.5 scenario simulations. The large-ensemble simulations were constructed with perturbed initialization (Mitchell et al 2017). ERA-Interim reanalysis data (Dee et al 2011) are used to evaluate models at simulating summer season characteristics and timing.

To check robustness of results from AGCM-based HAPPI simulations, we also use simulations from atmosphere-ocean coupled GCMs participating in the CMIP5 (Taylor et al 2012). Eight CMIP5 models (42 ensemble members) are used, which provide daily temperature data and have at least three ensemble members for the Representative Concentration Pathway (RCP) 8.5 scenario experiment (table S1 (available online at stacks.iop.org/ERL/17/014012/mmedia)). For each model, 10 year periods corresponding to Plus15 and Plus20 conditions are selected as follows. Based on the estimated observed global warming of 0.87 °C from pre-industrial period (1850–1900) to the current period (2006–2015) as reported by IPCC (2018), we find 10 year periods when the 10 year mean global mean surface temperature reaches additional warming of +0.63 °C and +1.13 °C relative to the current period (2006–2015), respectively, for Plus15 and Plus20 conditions. In most of the models, the period selected occurs
predominantly during 2020–2030s for Plus15 and 2030s–2040s for Plus20 (table S1). Similar methods have been used in many studies (Schleussner et al 2016, Lee et al 2018, King et al 2020), which help to reduce possible inter-model uncertainties related to different warming rates during the historical period.

For fair comparison with HAPPI-based results, we used 10 year periods for the CMIP5 analysis. However, there could be a concern whether the 10 year period is sufficient to determine the length of summer in model simulations considering that the CMIP5 models exhibit inherent natural decadal variability, while the HAPPI simulations are forced by observed decadal variations. To address this concern, we have checked the influence of period length by selecting 20 year periods from Plus15 and Plus20 conditions from CMIP5 model simulations and repeating our analyses. Results remain unchanged (not shown), indicating negligible influences of the time slice period.

2.2. Summer season indices
The summer season indices were defined by the relative thresholds at each grid point over the extratropical NH land located north of 23.5° N where an annual cycle is clearly observed (see Christidis et al 2007, Park et al 2018). After removing the daily variability of temperatures by fitting to fourth harmonic function following Weller et al (2020), we defined the 75th percentile of temperature values as a relative threshold of summer temperature on each grid point, which corresponds to ‘the warmest quarters of the year’ (Trenberth 1983). The local temperature threshold is calculated from the climatology of All-Hist runs and applied to Plus15 and Plus20 to estimate future changes in summer season indices on each model base. As indicated in figure 1(a), the summer onset and withdrawal dates are defined as the timing of intersecting points of the temperature threshold and smoothed seasonal cycle. Subsequently, the summer duration can be obtained as total number of days from onset to withdrawal.

The occurrence of hot days, like those in the middle of summer, is expected to increase in direct response to prolonged summer seasons in a warmer world, which would have important implications for human society as well as the ecosystem. To measure future changes in ‘summer-like’ days near the boundaries of the summer season, we count the number of days with temperatures higher than the summer mean temperature (figure 1(b)). In order to consider different degrees and patterns of summer expansion across regions, this calculation is done in a relative way on each grid by considering the two periods of advanced summer onset and delayed summer withdrawal. Here, expanded periods are determined based on the future summer season length (Plus20) with respect to All-Hist (figure 1(b)). Further, we check how different day-to-day fluctuations of temperature affect future change patterns in frequency of summer-like days across NH regions. For this, standard deviations (SD) of daily temperatures during the extended edges of summer season are calculated, for which the fourth harmonic filtered seasonal cycle is removed a priori.

Nine spatial domains over the NH extratropical lands are considered spanning hemispheric to subcontinental scales (figure 1(c)), following Park et al (2018): (a) the whole NH land areas north of 23.5° N, (b) NH high latitudes (50°–85° N, NH1) and mid-latitudes (23.5°–50° N, NH2), and (c) six sub-continental regions: Northern Europe (50°–85° N, 10° W–60° E), the Mediterranean (23.5°–50° N, 10° W–60° E), Northern Asia (50°–85° N, 60° E–170° W), East Asia (23.5°–50° N, 60° E–170° W), Canada (50°–85° N, 170°–10° W), and the United States (23.5°–50° N, 170°–10° W). NH1 and NH2 are constructed by combining three sub-continental domains located in the respective latitude bands (figure 1(c)).

3. Results
3.1. Hemispheric changes in summer season indices
The HAPPI All-Hist climatology of summer onset and withdrawal dates are displayed in comparison with those from ERA-Interim reanalysis (figure 2). In the reanalysis, on average the summer begins around June 5th and ends around September 3rd yet with large deviations across regions. Generally, the earlier start and end of summer season is observed over the high-latitude lands including Greenland, Alaska, and Northeastern Russia rather than the mid-latitude

Table 1. List of AGCM models from the HAPPI project. Each model’s All-Hist ensemble mean biases in NH mean summer onset (ONS) and withdrawal (WIT) dates with respect to ERA-Interim values are provided.

| Model   | Institution | Ensemble members | Horizontal resolution (Lon. x Lat.) | NH mean ONS bias (days) | NH mean WIT bias (days) |
|---------|-------------|------------------|-----------------------------------|------------------------|------------------------|
| CanAM4  | CCCma       | 100              | 128 × 64                          | –0.56                  | –0.86                  |
| CAM4    | ETH         | 501              | 144 × 96                          | +3.13                  | +3.92                  |
| MIROC5  | MIROC       | 100              | 256 × 128                         | +0.92                  | +1.17                  |
| ECHAM6.3| MPI-M       | 100              | 192 × 96                          | +2.22                  | +2.62                  |
| NorESM1 | NCC         | 125              | 288 × 192                         | +4.47                  | +4.72                  |

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lands like continental USA and the Mediterranean. Coastal areas tend to have relatively later onset and withdrawal than inland areas, indicating its delayed response due to stronger influence of adjacent oceans with large heat capacity (e.g. Mann and Park 1996). Due to the topographic effect, particularly near the Himalayas, earliest summer occurs over the Tibetan plateau. HAPPI runs reproduce well the observed average timing of summer season with a slight delay (<+2 d) and their regional variations with high spatial correlation (>0.8). CMIP5 models exhibit good skills comparable to HAPPI models, reproducing the observed spatial details of summer onset and withdrawal dates (figure 2).

HAPPI-simulated future changes in NH mean summer season indices are examined. Figure 3(a) displays the distributions of summer season onset and withdrawal dates (histograms) for All-Hist (blue), Plus15 (green), and Plus20 (red) for 5 HAPPI models, obtained from using all ensemble members with respect to their All-Hist mean values (see table 1 for NH mean biases). Figure 3(b) further summarizes each model's ensemble mean (x marks) together with multi-model means (diamond marks). All five HAPPI models simulate increased lengthening of the summer season under stronger warming, such that multi-model means project earlier summer onset by 4.4 d and 8.1 d and delayed summer withdrawal by 5.4 and 9.2 d for Plus15 and Plus20, respectively. The summer expansion could be seen as relatively symmetric but a slightly longer expansion in the withdrawal occurs (see below for details). The large spread of each histogram indicates that there are substantial intra-ensemble differences in all HAPPI models, which can represent different future changes in NH mean summer season onset and withdrawal of up to 2 d, implying an important role from internal variability (Yettella and England 2018). MIROC5
Figure 2. The current decade (2006–2015) climatology dates of summer onset (left) and withdrawal (right) from ERA-Interim reanalysis (top), HAPPI models (middle), and CMIP5 models (bottom). Multi-model means are displayed for HAPPI (5 models) and CMIP5 (8 models). Mean values for the NH lands are given below each map, and values in the top-right of each map represent spatial correlation of multi-model means with ERA.

Figure 3. (a) Histograms of NH land area averaged summer onset (left) and withdrawal (right) dates for All-Hist (blue), Plus15 (green) and Plus20 (red) experiments from 5 individual HAPPI models. Units are days relative to the current period climatology (zero vertical lines). (b) Distributions of each model ensemble mean for HAPPI (x mark) and CMIP5 (+ mark) are indicated together with their multi-model means (diamond mark).
shows largest changes while ECHAM6-3-LR exhibits smallest changes, and somewhat clearer in summer onset (x marks in figure 3(b)). Accordingly, inter-model differences are larger for summer onset (∼3 d) than for summer withdrawal dates (∼2 d).

CMIP5 models show largely similar projection results in NH mean summer season lengthening (plus marks in figure 3(b)). However, they tend to project slightly larger changes than HAPPI results by about 0.3–0.5 d for both summer onset and withdrawal. The stronger summer expansion in CMIP5 is found to be related to stronger warming over the NH land areas during summer (May to September; figure S1), which might be partly due to the stronger warming over land in the transient climate than in the near equilibrium climate (King et al. 2020). Also, as Mitchell et al. (2017) reported, HAPPI model simulations could have current decade (All-Hist) warm biases due to the cold ocean conditions associated with the negative phase of Pacific Decadal Oscillation, which may portray stronger warming over ocean in the future and in turn weaker warming over land in HAPPI projections. In addition, CMIP5 models show larger inter-model spread than HAPPI models, which is not surprising considering the diverse ocean states simulated in CMIP5 models in contrast to the same ocean condition prescribed in HAPPI models. An extensive investigation into further factors driving the inter-model differences is warranted in future analysis.

3.2. Regional changes in summer season indices

In order to assess regional changes, current and future summer onset and withdrawal dates from HAPPI models (multi-model means) are compared for the nine spatial domains (figure 5). Blue, green and red horizontal bars indicate results for All-Hist, Plus15 and Plus20, respectively. Corresponding CMIP5 results (plus marks) and ERA-Interim reanalysis climatology (yellow square marks) are
Figure 5. Regional and hemispheric domain averaged dates of summer onset (left) and withdrawal in All-Hist, Plus15 and Plus20 experiments from HAPPI (horizontal bars) and CMIP5 (+ marks) multi-model means. Results from ERA-Interim reanalysis (yellow squares) are provided for comparison. Future change values of summer onset and withdrawal (unit: days) are indicated for Plus15 and Plus20 for HAPPI (colored font) and CMIP5 (black font in parentheses).
and summer delay by about 3–5 d across all NH land regions. Larger global warming mitigation benefits are expected in mid-latitudes than high latitudes such that all regions could experience additional expansion of summer season by about 6 d in high latitudes (NH2) and 8–9 d in mid-latitudes (NH1), consistent with future projection patterns of an additional half a degree (figures 4 and 5). The largest benefits of global warming mitigation are projected in the Mediterranean and smallest change in Northern Asia. Overall, HAPPI and CMIP5 models provide very similar results in terms of spatial patterns and regional mean estimates, implying that the estimated benefit of reduced summer season length may be largely unaffected by the model samples analyzed (i.e. AGCMs vs coupled GCMs). Also, both summer onset and withdrawal contribute to the potential benefits with comparable magnitudes ranging from 2.6 to 4.6 d, depending on domain. It is noted that this is also different from the asymmetric warming patterns found in future changes, indicating a rather symmetric nature of the responses to additional half a degree warming.

3.3. Changes in summer-like days
To investigate the impact of global warming on hot day events, we examine changes in the frequency of ‘summer-like’ days during the expanded period of future summer seasons (refer to section 2 for its definition). The advanced onset and delayed withdrawal

![Figure 6](image-url)
periods are selected based on the difference between Plus20 and All-Hist as explained above (figure 1(b)), and the number of summer-like days are counted within the extended periods of summer onset and withdrawal, respectively. This calculation is conducted for each model run and then averaged across multiple models. Figure 7 displays spatial distributions and regional means of the resulting frequency of summer-like days for All-Hist, Plus15, and Plus20. In the current decade (figure 7(a)), summer-like days are rarely observed, on average about twice a year (i.e. a single day per year in extended onset period and another day in extended withdrawal period). There are large differences across regions with higher frequency (>3 d for onset or withdrawal) in low latitude regions including Southern China, Northeastern Africa, and Mexico, and with lower frequency (<0.5 d for onset or withdrawal) over higher latitudes including western USA, Greenland, and eastern Russia. Central Europe experiences relatively more frequent summer-like days (>2 d) than the other regions located in similar latitudes. Generally, summer-like days occur more frequently around summer onset than withdrawal, which can be clearly seen from regional mean frequencies (figure 7(b), blue bars). This difference is related to the stronger day-to-day variability of temperature near onset dates than near withdrawal dates (see figure 8 below).

Plus15 and Plus20 results show that summer-like days will become 2–3 times more frequent over the entire NH with stronger increases in low latitudes and over western Eurasia, following the current climatology pattern (figure 7(a)). Regions with larger summer season lengthening tend to have

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**Figure 7.** (a) The spatial distributions of summer-like day frequency (unit: days per year) during extended summer onset (left) and withdrawal (right) period in All-Hist, Plus15, and Plus20 experiments from HAPPI (above) and CMIP5 (below) multi-model means. (b) Domain averages of the frequency of summer-like days in All-Hist (blue), Plus15 (green) and Plus20 (red) from HAPPI (colored bars) and CMIP5 (+ marks) multi-model means.
stronger increases in summer-like day frequency, such as the USA, Mediterranean, and East Asia (figure 7(b)). When comparing summer-like day frequencies between summer onset and withdrawal periods, many regions show comparable increases, indicating a somewhat symmetric impact of additional warming on the hot day frequency in both edges of summer season. One exception is that of East Asia, where stronger increases are projected during extended withdrawal than during extended onset. This is seen for both Plus15 and Plus20, resulting in stronger changes of more than 3 d for both onset and withdrawal.

CMIP5-based results mostly resemble those from HAPPI with a few noticeable differences. In the current decade, more frequent summer-like days are simulated over high-latitude regions and less frequent summer-like days over East Asia in CMIP5 models. Plus15 and Plus20 results indicate that CMIP5 models predict larger increases in summer-like day frequency in several regions, including Mediterranean, USA, and Canada. Interestingly, stronger changes are seen during withdrawal periods than during onset periods, which contribute to more symmetric increases in summer-like day frequency in CMIP5 models than HAPPI. Such differences in projections of summer-like days appear to be related to the differences in temperature increases near the summer season edges as pointed out above.

In order to check if daily temperature variability affect the changes in summer-like day frequencies, we obtain spatial distributions of the standard deviation (SD) of daily temperature during expanded summer periods (figure 8(a)). Note that, before calculating the SD, the seasonal cycle has been removed from raw daily temperatures to only focus on the day-to-day variabilities in corresponding expansion periods. For both onset and withdrawal periods, lower latitudes possess smaller daily variability than high latitudes (as one may expect), indicating the important role of smaller daily variability in lower latitudes in the higher frequency in occurrence of the summer-like days. Negative spatial correlations between the SD and the frequency of summer-like days for both onset and withdrawal ($r_s = -0.40$ and $-0.56$, respectively) support this.

The strong influence of daily temperature variability is confirmed when comparing present-day SD
with future frequency of summer-like days using regional means (figure 8(b)). High-latitude regions (open marks) tend to have stronger daily temperature variability than mid-latitude regions (filled marks), more clearly in withdrawal period. Inter-region correlations between present-day SD and future frequency of summer-like days are strong, being \(-0.71\) and \(-0.97\) for onset and withdrawal, respectively, both of which are significant at 5% level. Similar results from CMIP5 models support the importance of daily temperature variability in determining future frequencies of summer-like hot days, despite some regional differences compared to HAPPI in East Asia and the Mediterranean and the weaker inter-region correlation \((-0.24\) and \(-0.57\) for onset and withdrawal, respectively).

### 4. Summary and conclusions

Using multiple climate model simulations, this study examined future changes in summer season length and timing under 1.5 \(\degree\)C and 2.0 \(\degree\)C global warming conditions (above pre-industrial level) over the NH land areas. This also enabled an assessment of the benefits from mitigation efforts of global warming. Results are mainly based on five AGCM large-ensemble simulations available from the HAPPI project, which provide more than 100 ensemble members for each model for a current decade (2006–2015; All-Hist) and a future decade corresponding to the 1.5 \(\degree\)C and 2.0 \(\degree\)C warmer conditions (Plus15 and Plus20). Eight CMIP5 coupled GCM simulations were also used to assess the robustness of HAPPI-based results by finding future decades corresponding to 1.5 \(\degree\)C and 2.0 \(\degree\)C conditions based on RCP8.5 scenario simulations. For each model, local temperature thresholds were obtained on a grid basis using the All-Hist climatology, which were used to define summer season onset, withdrawal, and duration and examine future changes. Nine spatial domains encompassing the whole NH, NH mid- and high-latitudes, and six sub-continental regions (Canada, USA, Northern Europe, Mediterranean, North Asia, and East Asia) were considered.

HAPPI and CMIP5 models reproduced well the observed characteristics (pattern and timing) of summer season indices, including earlier onset and withdrawal more inland than the coastal areas. Results of the future decades show that summer season length is projected to increase everywhere, from a few days to weeks, under 1.5 \(\degree\)C and 2.0 \(\degree\)C warmer conditions. Larger advancement of summer onset and delay of summer withdrawal are simulated for mid latitude lands, in particular, over East Asia and the Mediterranean, than for high latitude lands. The general Arctic amplification of global warming is dominant during winter (e.g. Cohen et al 2020) while the amplitude of summer warming is equivalent across mid- to high-latitude land areas. Because of the larger amplitude of seasonal cycle, the impact of similar temperature warming leads to smaller change in summer season length over high-latitudes than in mid-latitudes. In addition, larger changes were found in summer withdrawal than in summer onset, and CMIP5 models tend to produce stronger increases, which were found to be associated with regional differences in temperature increases. To measure the possible benefit of global warming mitigation by an additional half a degree, differences in future changes to summer season indices between Plus15 and Plus20 were compared. Mid-latitude regions, where the summer expanded more strongly, were found to benefit most in terms of summer season expansion than high latitude regions. Unlike the asymmetric changes with stronger expansion in summer withdrawal than in summer onset, additional changes due to the half a degree additional warming were found to be similar, indicating overall symmetric response in the differences.

To translate the actual impact of summer season lengthening on everyday weather, further analysis was conducted whereby future changes in the number of ‘summer-like’ days (defined based on summer mean temperatures from All-Hist) during the extended boundaries of summer season were measured. In accord with the spatial patterns of summer season lengthening, the summer-like days are projected to occur more frequently, by 2–3 times compared to the current frequency, and more strongly in mid-latitude regions. Further, it was shown that day-to-day variability in temperatures is an important factor determining the regional differences in the hot day frequencies. For example, regions with lower daily variability exhibit a stronger increase in summer-like days, and vice versa. However, the increased frequency of summer-like days will decrease if limiting global warming by half a degree can be achieved. Again, similar results were obtained from CMIP5 models, suggesting that the findings are not a factor of model sampling.

Our results present a first multi-model based assessment of possible impacts of Paris Agreement temperature targets on the summer season duration and associated frequencies of summer-like days across NH regions, providing a quantification of the possible benefits of global warming mitigation. Our quantified projections of future seasonal cycle timing will be useful for the climate impact community to carry out specific risk assessments for agriculture, water resources, ecosystem, energy etc. A follow-up analysis of Southern Hemisphere seasonal length and timing will be conducted as a separate study, in which future ocean changes and its regional impacts need to be considered with care. In addition, summer expansion over ocean and its impact on ecosystems needs to be investigated comprehensively in line with the increasing marine heat waves (Frölicher et al 2018, Holbrook et al 2019).
Data availability statement

No new data were created or analysed in this study.

Acknowledgments

This study was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (NRF-2018R1A5A1024958 and NRF-2021R1A2C3007366). Daily surface air temperature data are available on the database of ERA-Interim (https://apps.ecmwf.int/data sets/data/interim-full-daily/levtype=sfc/), HAPPI simulations (http://portal.nersc.gov/c20c/data.html), and CMIP5 simulations (https://esgf-node.llnl.gov/projects/cmip5/).

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