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Earlier green-up and spring warming amplification over Europe

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Abstract

The onset of green-up of plants has advanced in response to climate change. This advance has the potential to affect heat waves via biogeochemical and biophysical processes. Here a climate model was used to investigate only the biophysical feedbacks of earlier green-up on climate as the biogeochemical feedbacks have been well addressed. Earlier green-up by 5 to 30 days amplifies spring warming in Europe, especially heat waves, but makes few differences to heat waves in summer. This spring warming is most noticeable within 30 days of advanced green-up and is associated with a decrease in low- and middle-layer clouds and associated increases of downward short wave and net radiation. We find negligible differences in the Southern Hemisphere and low latitudes of the Northern Hemisphere. Our results provide an estimate of the level of skill necessary in phenology models to avoid introducing biases in climate simulations.

Introduction

The timing of biological events including leaf emergence, leaf senescence, fruiting, and flowering is sensitive to climate change [*Richardson et al.,* 2013; *Piao et al.*, 2015]. The Fourth Assessment Report (AR4) [*Parry et al.*, 2007] of the Intergovernmental Panel on Climate Change found that spring onset has been advancing by between 2.3 and 5.2 d per decade since the 1970s. *Rosenzweig et al.* [2007] concluded that these changes in vegetation phenology "are perhaps the simplest process in which to track changes in the ecology of species in response to climate change." In temperate forests, modeling and remote sensing studies suggest rapid rates of advance (1.8–7.8 d/decade) of spring green-up in recent decades, although considerable variability among species and between studies has been reported [*Richardson et al.*, 2006; *Jeong et al.*, 2011]. *Zeng et al.* [2011], using Moderate Resolution Imaging Spectroradiometer (MODIS) (MOD13C1 at 0.05°) and advanced very high resolution radiometer (at 8 km × 8 km resolution), detected an earlier start of the growing season by 4.7 d per decade over the Northern Hemisphere high latitudes. Studies focusing on the boreal region reported rates of advancement of between 2 and 14 d/decade in spring onset in more recent decades [*Delbart et al.,* 2008].

The presence of green land cover earlier in the season has the capacity to alter the seasonal climate through the effects of biogeochemical (especially photosynthesis and carbon sequestration) and physical processes (the surface energy and water balance) of vegetated land surfaces [*Penuelas et al.*, 2009; *Richardson et al.*, 2013]. However, as highlighted by *Richardson et al.* [2012] existing models capture phenology poorly. In addition, the biophysical effects of any change in vegetation phenology on energy partitioning between latent and sensible heat fluxes are not well documented. Evidence exists that an earlier green-up may enhance the likelihood of summer drought because soil water is depleted earlier in the growing season [*Kljun et al.*, 2006; *Hu et al.,* 2010]. For Europe, previous modeling and observation studies have suggested that an earlier onset of vegetation green-up and a prolonged period of increased evapotranspiration have enhanced recent summer heat waves by lowering soil moisture [*Zaitchik et al.*, 2006; *Fischer et al.*, 2007]. *Stéfanon et al.* [2012] found that in Europe during 2003, the earlier green-up dampened the temperature anomaly in June (boreal summer), while it amplified the temperature anomaly in August. Also for Europe, *Lorenz et al.* [2013] found that weak greening amplifies heat waves while spring greening and the associated increase in leaf area index tended to dampen heat waves.

While observational evidence exists of changes in the timing of phenology, whether the changes are large enough to affect simulations by climate models is unknown. If a climate model captures the spring green-up but captures this 1 month too early, does this result in significant errors? Is 20 days close enough or 10 days? Our objective is to determine the necessary accuracy as this then informs climate modelers of the likely sophistication required in a phenology model. In addition, we also investigate two hypothesis suggested by previous studies: (1) Does earlier green-up enhance the evapotranspiration and dampen the spring warming? And (2) does earlier green-up lead to increased early-season transpiration and late-season dryness that increases the probability of hot extremes?

Methods

Model Description

We used the Australian Community Climate Earth System Simulator version 1.4 (ACCESS1.4). ACCESS1.4 consists of the atmospheric Unified Model (UM7.3) [*Davies et al.*, 2005], land surface model (CABLE 2.2.3), the Modular Ocean Model, and a coupling framework that couples the ocean and sea ice to the atmosphere [*Bi et al.*, 2013]. ACCESS1.4 is an updated version of ACCESS1.3, which has been extensively evaluated [*Bi et al.*, 2013; *Kowalczyk et al.*, 2013; *Lorenz et al.*, 2014]. While the Community Atmosphere Biosphere Land Exchange (CABLE) [*Wang et al.*, 2011] was updated to include a dynamic phenology model and carbon-nitrogen-phosphorous cycle module [*Wang et al.*, 2010], we do not use these modules because vegetation phenology is commonly poorly represented in land surface models [*Richardson et al.*, 2012]. A key purpose of this paper was to examine how differences in spring phenology impact simulations later in the season. This provides guidance on how well the new vegetation phenology needs to be and helps to set a benchmark for model evaluation. Following *Lorenz et al.* [2014], we use prescribed sea surface temperatures and sea ice fractions in an Atmospheric Model Intercomparison Project-style configuration [*Gates*, 1992]. These data were sourced from the Program for Climate Model Diagnosis and Comparison [*Taylor et al.*, 2000] and regridded and converted to the Unified Model data format. We performed simulations at 1.25° latitude by 1.875° longitude resolution (N96 resolution) globally, with 38 vertical levels, and a 30 min time step.

Experimental Design

Leaf area index (LAI) is a good proxy for vegetation status and is used in land surface models to present vegetation phenology. A monthly climatological LAI, derived from the MODIS TERRA MOD15A2 and AQUA MYD15A2 (8 day and 1 km) products over the period of 2000–2009 [*Zhu et al.*, 2013], was used in the Control simulation (CTRL), which is common practice when running ACCESS (and most climate models). We performed four experimental runs by manipulating LAI to represent the earlier greening seasonal cycle. We assume an advancement from 5 days to 30 days as a realistic approximation of leaf green-up in response to spring warming because previous observation and modeling studies reported the leaf green-up advanced at 1.6–14 d per decade, which varies between regions and species. In our four experiments we shift the LAI toward earlier green-up by 5 days (5d), 10 days (10d), 20 days (20d), and 30 days (30d) as shown in Figure S1 in the supporting information. We performed five ensembles for CTRL and each experiment by initializing the model runs 1 year apart to generate a range of initial conditions. The first ensemble starts in 1952 and the last ensemble in 1956, and all end in 2005. The common period 1966–2005 was used for our analysis, omitting the first ~10 years as spin-up.

Analysis Methodology

Temporal and Spatial Averaging

We explored results at 5 days, 10 days, 20 days, and 30 days as well as seasonal means. We focus on Northern Hemisphere spring because we did not find trends in other seasons. Our analysis focused on Europe, which was further divided into two subregions (Figure 1c) because we did not find substantial effects in the Southern Hemisphere and low latitudes of the Northern Hemisphere.

Hot Extreme and Heat Wave Indices

We computed hot extreme and heat wave indices during spring to examine the impact of early green-up. Hot extremes were defined as the maximum of daily Tmax in spring (TXx). Following *Perkins and Alexander* [2013], we define heat wave days as days when temperatures exceed the 90th percentile of the daily maximum temperature (TX90p) for at least three consecutive days. The percentiles are computed for each calendar day with a 15 day moving window over a 30 year reference period (defined as 1961–1990 from the CTRL simulation). The heat wave duration is defined as the length of the heat wave events in days, and the heat wave exceedance is the magnitude of the temperature exceeding the TX90p.

Statistical Methods

The modified *t* test [*Zwiers and von Storch*, 1995] was used to identify whether the difference between experiments and control run is statistically significant. The modified *t* test accounts for autocorrelation within the time series [*Zwiers and von Storch*, 1995].

The probability density functions (PDFs) for Tmax were computed to investigate which of the distributions are substantially different between the experiments and the control simulations, with a particular focus on the tails of the distributions, which describe the probability of hot or cold extremes. We use *R*'s kernel density function, using the default Gaussian smoothing kernel option and a bandwidth estimated via normal reference distribution. The Kolmogorov-Smirnov test in *R* was used to test whether the distributions between each experiment and the control simulation are statistically significantly different.

Results

We focus on Europe in spring as discussed in section 2. First, we present the impact of earlier green-up on the surface climatology followed by the impacts on heat waves.

The Impact of Earlier Green-Up on the Mean Climate

The earlier green-up leads to higher daytime temperatures in spring (Figure 1) but makes little difference to nighttime temperatures (not shown). The 10d experiment leads to an increase of Tmax (~0.25°C) in Europe relative to the CTRL (Figure 1a). There is no substantial difference between the 10d and 20d experiments (Figure 1b). In the 30d experiment there is a noticeable increase in Tmax of ~0.7°C over large areas of Europe, reaching 1°C in some areas compared with CTRL (Figure 1c). Some of this increasing impact is related to the length of time the green-up is perturbed since the 10d experiment is imposed for 10 days, while the 30d experiment is imposed for 30 days, and consequently, a larger impact is expected. However, the larger changes for the 30d experiment also relate to feedbacks on clouds and radiation discussed later.

The difference between the TXx and CTRL is shown in Figures 1d–1f. TXx increases 0.8°C on average and more than 1.3°C in some areas in the 10d experiment (Figure 1d). In some regions, including the UK, Ireland, and around the Black Sea, TXx is decreased in the 10d experiment compared to CTRL, but these decreases are rarely statistically significant. There is a relatively smaller increase of TXx (~0.6°C) in the 20d experiment, compared to the 10d experiment (Figure 1e). The experiment 30d strengthens the increase of TXx, which increases to more than 1°C over large areas of central Europe relative to the CTRL (Figure 1f). These increases are statistically significant over widespread regions.

The Impacts of Earlier Green-Up on the Probability Density Functions of Tmax

The strong increase of TXx indicates that earlier green-up leads to hotter extremes in spring, which is confirmed by PDFs of Tmax for the experiments and the control run (Figures 1g and 1h). The PDFs of the experiments in central Europe (CE, defined in Figure 1c) are shifted toward the upper tail of the distribution relative to the control run (Figure 1g), and this shift is statistically significant. The 5d experiment distribution shifts toward the right side of the CTRL distribution, but the upper tail shares the same probability density as the CTRL. The 10d experiment distribution is further shifted to the right side of the CTRL distribution, relative to the 5d experiment. The 20d experiment is very similar to the 10d experiment. The 30d experiment substantially shifts the distribution to the right relative to the CTRL distribution. Noticeably, the 30d experiment distribution has a longer upper tail than the CTRL.

In Eastern Europe (Figure 1h), the distributions are again generally shifted toward the right relative to the CTRL. The 10d experiment distribution is shifted by approximately 1°C toward the right. There is little difference between the distribution of the 10d and 20d experiments. Again, the shift of 30d distribution is strongest compared to the other experiments and has a longer upper tail. The changes for 10d, 20d, and 30d are statistically significant.

Impact of Earlier Green-Up on Heat Waves

The shift of the PDFs to the upper tail with the earlier green-up could lead to a change in the frequency and intensity of heat waves. Figure 2 shows an increase in heat wave frequency, duration, and intensity, especially for the 30d experiment. There is an increase in the frequency of heat wave events due to the earlier green-up (Figures 2a–2c), by around 0.3 events in 10d and 20d experiments, and these two experiments share similar spatial patterns (Figures 2a and 2b). In the 30d experiment, there are 0.6 more heat wave events per season on average.

The duration (number of consecutive days above the threshold) and intensity (the magnitude of Tmax exceeding the TX90p during an event) of heat wave events also respond to the earlier green-up (Figures 2d–2i). The increase in heat wave duration (~0.5 day) in the 10d and 20d experiments shares a similar pattern. In the 30d experiment, there is an increase of the heat wave duration over large parts of Europe by 1 day on average. In France, the increase in duration of heat wave events exceeds 1 day and occasionally 2 days with the 30 days earlier green-up experiment (Figure 2f).

The heat wave intensity generally increases relative to CTRL. The increase of heat wave intensity (~0.5°C) is not substantially different between the 10d and 20d experiments (Figures 2g and 2h). The 30d experiment increases the heat wave intensity further, by about 1°C on average, and the increase of heat wave intensity reaches 1.5°C in France and other parts of Western Europe (Figure 2i).

Mechanisms

The first-order impact of the earlier green-up is on the partitioning of available energy between latent and sensible heat, and the partitioning of latent heat between ground evaporation and canopy evapotranspiration. The reallocation of latent heat into canopy transpiration and ground evaporation energy is shown in Figures 3a–3f. The earlier green-up leads to a decrease in ground evaporation by about 4, 7, and 9 W m^{-2} in the 10d, 20d, and 30d experiments, respectively (Figures 3a–3c). In contrast, the canopy evapotranspiration increases with a similar spatial pattern and magnitude (Figures 3d–3f). In total, the latent heat flux decreases by around 2 W m^{-2} (Figures 2g–2i) and is statistically significant in central Europe for experiments 20d and 30d.

In addition to the reallocation of the latent heat from ground evaporation to canopy transpiration, the earlier green-up also leads to a decrease of low-layer (below 2 km) and middle-layer (2–6 km) clouds (Figures 4a–4f). There is a near-linear decrease of low cloud of about 2, 3, and 4% in 10d, 20d, and 30d experiments, respectively. The decrease of low cloud in the 30d experiment is more than 10% relative to the absolute cloud fraction (~30%) of the CTRL. In contrast, the middle-layer cloud shows a nonlinear response to the earlier green-up. There is a decrease of middle-layer cloud in the 10d and 30d experiments in central Europe (Figures 4d and 4f), but there is no substantial change in the 20d experiment in central Europe (Figure 4e). As a result, the decrease of clouds leads to a nonlinear increase of total downward short wave radiation (Figures 4g–4i). In Eastern Europe, the total downward short wave radiation shows a linear increase of about 5, 7, and 9 W m^{-2} on average for the 10d, 20d, and 30d experiments, respectively (Figures 4g–4i). In contrast, the total downward short wave radiation in central Europe shows a lower increase and a nonlinear response to the earlier green-up. There is an increase of 2 and 4 W m^{-2} total downward short wave radiation for the 10d and 30d experiments in central Europe.

In summary, the small decrease in the latent heat and the increase of sensible heat lead initially to a decrease in low clouds, and consequently, more short wave radiation reaches the surface, which warms the surface. The warmer surface leads to a further decrease of low cloud as well as middle cloud—a positive feedback that amplifies the initial change in the latent heat flux. As a result of the increase in short wave and thus net radiation, and the small decrease of latent heat flux, there is an increase in sensible heat (not shown), which contributes to the increase in daytime temperature and in particular hot extremes.

Discussion and Conclusion

It has been suggested that earlier green-up could enhance evapotranspiration and dampen springtime warming and could lead to late-season dryness that increases the probability of hot extremes [*Zaitchik et al.*, 2006; *Fischer et al.*, 2007; *Stéfanon et al.*, 2012]. We examined this hypothesis and investigated the effects of earlier green-up from 5 to 30 days using a global climate model. Our analysis was carried out from 5 days to the seasonal time scale to explore the short-term (5–30 days) and longer-term (months) impacts of earlier green-up.

An earlier growing season can dampen or amplify global warming, depending on water availability and regional characteristics [*Penuelas et al.*, 2009]. Specifically, the spatiotemporal cooling or warming effects of greenness are driven by two sets of effects: First, how does an earlier green-up affect surface albedo and biophysical processes that control the flow of moisture from land to the atmosphere? This surface energy balance change is commonly explored and reasonably well understood [*Boisier et al.*, 2012]. Second, how does a change in the surface energy balance couple with the planetary boundary layer, clouds, and short wave radiation? In the present study, we found that the initial impact on the surface energy balance led to amplifying feedbacks via cloud and short wave radiation such that the earlier green-up amplifies spring temperatures in Europe, especially central Europe. The earlier green-up has substantial impacts on daytime temperature, especially heat waves, but makes little difference on nighttime temperature because the reduction of low- and middle-level clouds and water vapor in the atmosphere enables a higher outgoing long wave flux at night which offsets any impact of higher daytime temperatures.

Our results do not show increases in the probability of summer hot extremes following the earlier green-up as proposed by previous studies [*Zaitchik et al.*, 2006; *Fischer et al.*, 2007; *Stéfanon et al.*, 2012]. We find that the canopy evapotranspiration is indeed increased in response to earlier green-up, but this is counteracted by a decrease of ground evaporation, a result similar to that reported by *Lorenz et al.* [2013]. In total, the latent heat flux is reduced by ~2 W m^{-2} and the impact on soil moisture is negligible (not shown). There is therefore no propagation of a drier soil from spring to summer and consequently no impact on summer heat waves. Linking changes in spring evaporation requires soil moisture trends to be simulated accurately, and of course, there are large uncertainties in predicting soil moisture by land surface models, especially in arid regions, and dry seasons [*Koster et al.*, 2009; *Seneviratne et al.*, 2013]. We did identify a very small drying trend due to the earlier green-up, but this was very small compared to internal model variability such that any signal is masked. Finally, we found that changes in canopy transpiration were compensated by changes in ground evaporation. This could be unrealistic and caused by model structural biases, a concern raised by *Lawrence and Chase* [2009] but difficult to quantify because of lack of observations that enable these two fluxes to be separately evaluated.

Tmax and the heat wave indices show a nonlinear response to the earlier green-up in our experiments. This closely links to the nonlinear effects of earlier green-up on middle-layer clouds, and the subsequent impact on total downward short wave radiation. Our results are consistent with *De Arellano et al.* [2012] who reported that lower latent heat fluxes and higher sensible heat fluxes due to the energy partitioning of plants leads to a decline in boundary layer cloud formation in midlatitudes. They also noted that the different plant functional types have different effects on cloud formation and particularly on low clouds [*de Arellano et al.*, 2014]. The earlier green-up and associated impacts on temperature also weakened the thermal gradient between the land and the ocean in spring. It is difficult to assess this result in detail since we used prescribed sea surface temperatures. However, this weakened thermal gradient could modify the regional circulation patterns with subsequent impacts on clouds. To examine this thoroughly would require coupled ocean modeling, which is beyond the scope of the current study.

Our focus here has been on the impact of earlier green-up on climate using a relatively simple experimental design that shifts the timing of the green-up forward in time. This is consistent with observations of earlier green-up. We do not attempt to modify the shape of the phenology profile or simulate the consequences of a higher risk of frost damage to plants that emerge earlier in the season [*Augspurger*, 2009]. These are important topics that might increase the impact of changes in phenology on regional climate and are priorities for future research. Although large uncertainties exist in the interaction between vegetation and clouds [*de Arellano et al.*, 2012, 2014], we conclude that in our model the nonlinear effects of shifting the seasonal cycle in LAI by 5 to 10, 20, and 30 days leads to nonlinear increases in total downward short wave radiation and increases in daytime temperature. Further studies investigating the impact of the land cover and land use change on clouds are clearly a priority [*de Arellano et al.*, 2014] to determine if our results are generalizable or model specific.

In conclusion, our results suggest the earlier green-up of vegetation in Europe amplifies spring warming, especially the frequency and intensity of spring heat waves. This warming effect is most noticeable with a 30 day advance but emerges with both a 10 day and 20 day advance. The impacts of earlier green-up in the Southern Hemisphere and in the low latitudes of North Hemisphere are negligible. Our results point to the level of precision required for models of phenology. Climate models simulate statistically significant increases in heat waves in spring for a 10, 20, and 30 days change, but not for a 5 day advance in green-up. Building phenology models for land surface schemes therefore likely need to achieve an accuracy of around 10–20 days which is challenging, but not as hard as developing skill to 5–10 days. Our results also highlight the necessity to move to using dynamic phenology in climate models. As climate change affects the timing of green-up by amounts that then affects regional climate, representing these changes in climate projections will lead to more complete and hopefully improved predictions in some key regions.

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Figure 1. Difference in (a–c) Tmax and (d–f) TXx between the experiments and the control in spring. (g and h) The probability density functions of Tmax for central (CE) and eastern Europe (EE), respectively. Stippling in Figures 1a–1f indicates areas where the difference is statistically significant based on the modified *t* test. The dashed lines in Figures 1g and 1h indicate that the experiment is statistically significantly different from the control run (Kolmogorov-Smirnov test, $p = 0.05$).

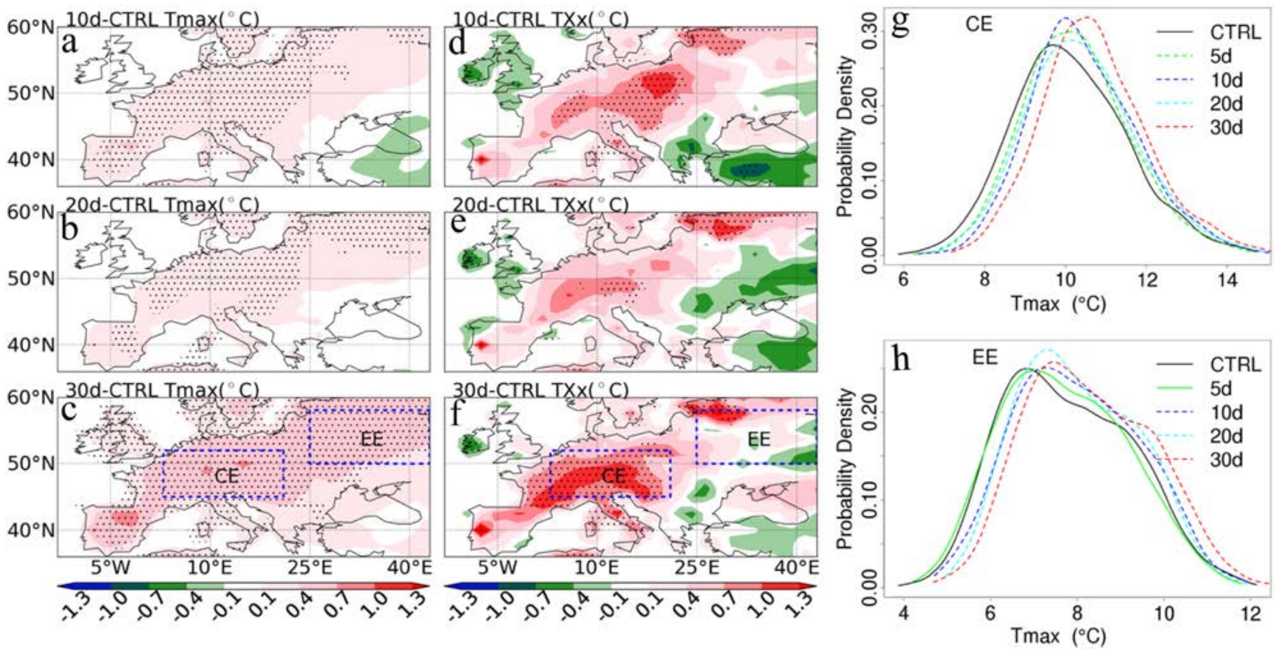

Figure 2. Difference in (a–c) heat wave events, (d–f) duration, and (g–k) intensity between the experiments and the control in spring. Heat waves are defined as a period of at least three consecutive days during which the maximum temperature (Tmax) exceeds the 90th percentile of Tmax. Stippling indicates areas where the difference is statistically significant based on the modified *t* test ($p = 0.05$).

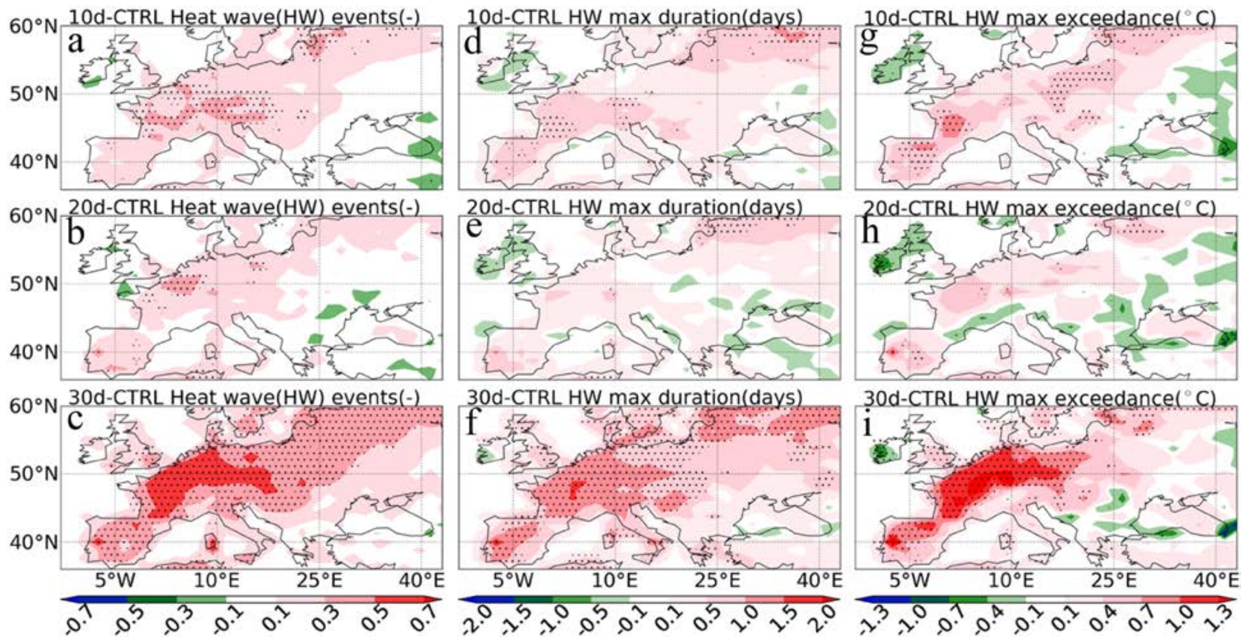

Figure 3. Difference in (a–c) ground evaporation, (d–f) canopy evapotranspiration, and (g–i) latent heat flux in spring between experiments and control. Stippling indicates areas where the difference is statistically significant based on the modified *t* test ($p = 0.05$).

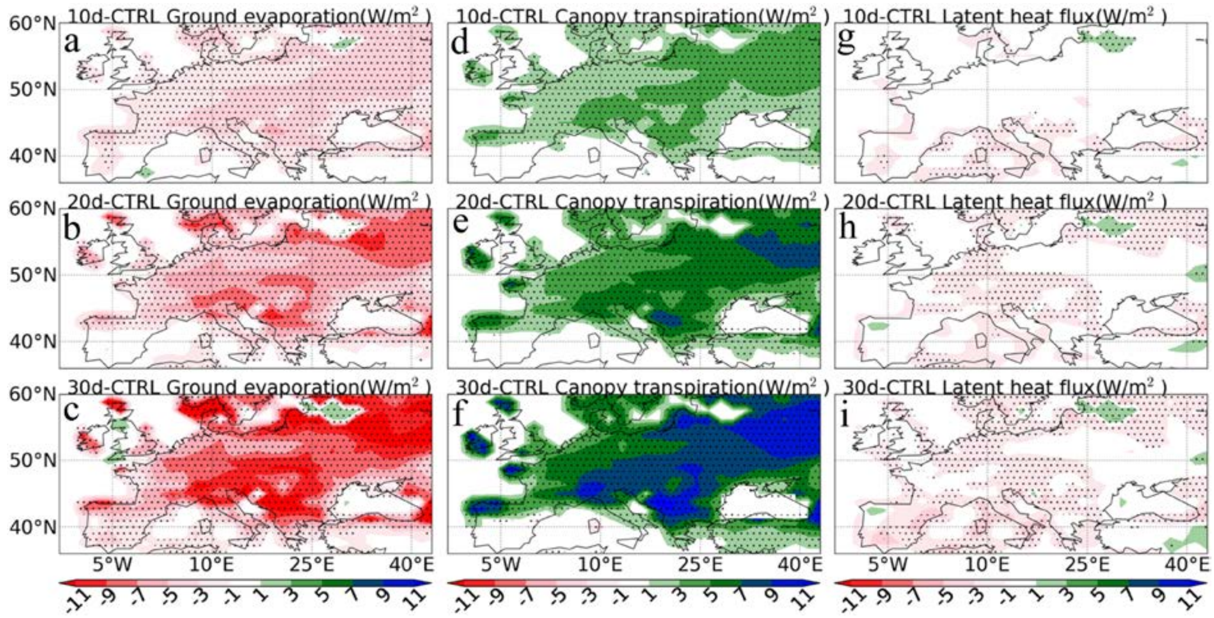

Figure 4. Difference in (a–c) low cloud (below 2000 m), (d–f) middle-layer cloud (2000–6000 m), and (g–i) total downward short wave radiation in spring between experiments and control. Stippling indicates areas where the difference is statistically significant based on the modified *t* test ($p = 0.05$).