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Modification of land-atmosphere interactions by CO₂ effects: implications for summer dryness and heatwave amplitude

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Key Points

1. Stomatal closure reduction under higher CO₂ concentration conserves soil water during springtime and increases temperature.
2. Springtime saved water enables increased transpiration and consequent temperature mitigation during the summer.

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3. Inclusion of CO₂ physiological effect is essential for future heat wave and seasonal prediction as it alters land-atmosphere feedbacks.

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Abstract

Plant stomata couple the energy, water and carbon cycles. We use the framework of Regional Climate Modeling to simulate the 2003 European heat wave and assess how higher levels of surface CO₂ may affect such an extreme event through land-atmosphere interactions. Increased CO₂ modifies the seasonality of the water cycle through stomatal regulation and increased leaf area. As a result, the water saved during the growing season through higher water use efficiency mitigates summer dryness and the heat wave impact. Land-atmosphere interactions and CO₂ fertilization together synergistically contribute to increased summer transpiration. This, in turn, alters the surface energy budget and decreases sensible heat flux, mitigating air temperature rise. Accurate representation of the response to higher CO₂ levels, and of the coupling between the carbon and water cycles are therefore critical to forecasting seasonal climate, water cycle dynamics and to enhance the accuracy of extreme event prediction under future climate.

1 Introduction

Western Europe experienced an unprecedented heatwave event and severe soil dryness conditions during the summer of 2003 [Schär *et al.*, 2004]. The impact on the ecosystems was widespread, as this event roughly negated four years of net carbon storage in Western Europe forests [Ciais *et al.*, 2005]. France experienced the highest temperature anomaly within Europe with mean daily temperatures in the 95th percentile from 8 to 16 June and from 2 to 16 August 2003 [Stéfanon *et al.*, 2012]. This meteorological episode had a great impact on society, as France, for example, recorded 15,000 excess deaths in August [Canoui-

Poitrine et al., 2006]. Such extreme heat waves are believed to occur more frequently [Quesada et al., 2012] and more intensely in future climate [Meehl and Tebaldi, 2004] in a context of globally warmer and locally drier conditions [Sherwood and Fu, 2014] in the mid-latitudes.

Land-atmosphere interactions play a fundamental control on the severity of those heat waves [Seneviratne et al., 2006; Fischer et al., 2007; Teuling et al., 2010]. There are several ways rising CO₂ levels affect the canopy conductance, which regulates both the water and energy cycles. First, the stomatal conductance is reduced with increasing surface CO₂ concentrations (Figure 1a), increasing the plant water use efficiency (WUE) [Ainsworth and Long, 2005; Morgan et al., 2011; Norby and Zak, 2011; Katul et al., 2012], defined as the ratio of net photosynthesis to transpiration. Reduced water vapor losses, in turn, conserve soil water and allows more heat to be dissipated as sensible heat flux, resulting in higher surface temperatures [Bateni and Entekhabi, 2012]. This effect is called the *stomatal response* (Figure 1a).

Second, the potential stimulation of biomass production by CO₂ fertilization [Ainsworth and Long, 2005; Mccarthy et al., 2007; Norby and Zak, 2011; Warren et al., 2011] can counteract some of the stomatal conductance reduction by increasing the leaf area [Wullschleger et al., 2002], hence sustaining higher transpiration and lower sensible heat flux, resulting in reduced temperature. This is referred to as *fertilization effect* (Figure 1b).

Numerous field experiments have been conducted to investigate the vegetation response to higher atmospheric CO₂ levels using various methodologies such as the Free-Air CO₂

Enrichment (FACE) experiments or using tree-rings isotopes [Saurer *et al.*, 2004; Norby and Zak, 2011; Peñuelas *et al.*, 2011; Frank *et al.*, 2015]. These experiments show that transpiration is typically reduced and water use efficiency increased with increasing CO₂, while local, above canopy temperature might increase due to higher sensible heating. Decrease in stomatal conductance accompanied by leaf area index (LAI) increase [Ainsworth and Long, 2005; Norby and Zak, 2011; Warren *et al.*, 2011] has been reported across several experiments and across a broad range of species. In particular, the stomatal conductance of crops and grass strongly and unequivocally responds negatively, i.e. the stomata close, to elevated CO₂ while maintaining relatively similar rates of photosynthesis [Ainsworth and Long, 2005]. As a result, the water-use efficiency of crops and grass have been reported to increase with elevated CO₂, the impact being even greater in water-stressed conditions [Wullschleger *et al.*, 2002]. The LAI increase can in some cases partly compensate some of the transpiration reduction by stomatal conductance [Wullschleger *et al.*, 2002; McCarthy *et al.*, 2007]. Higher LAI also increases canopy conductance so that more heat is released as turbulent heat fluxes (Figure 1b). Nonetheless individual species response to elevated CO₂ varies across FACE experiments. Multi-year droughts, in particular, may affect the availability of the deep soil moisture itself, as well as the biomass production stimulation and the capacity of trees to access the soil water [Morgan *et al.*, 2004; Warren *et al.*, 2011]. The Swiss Canopy Crane project - a long-term FACE experiment in a mature forest [Bader *et al.*, 2013] - is the only available on-site data for 2003 within the domain of our study. The elevated CO₂ plot showed notably reduced stomatal conductance and reduced transpiration in normal weather conditions (Figure 1a) [Keel *et al.*, 2007]. But during the 2003 centennial drought significantly higher transpiration was recorded for some species, translating into

locally reduced temperature during the extreme drought and heat wave [Leuzinger *et al.*, 2005]. The stomatal response during the growing season (Figure 1a) leads to a larger soil moisture availability later in the year, which could potentially decrease vegetation stress and increase evapotranspiration during a subsequent summer heat-wave and thereby mitigate its severity. This is referred to as *water cycle feedback* (Figure 1c).

These field experiments give crucial evidence at a small spatial scale of the different processes at play. Because of their small footprint, FACE experiments cannot be used to investigate the regional land-atmosphere impact of CO₂ fertilization nor the regional coupling and feedbacks with the atmosphere [Leuzinger *et al.*, 2015] that may, for instance, affect the atmospheric water vapor pressure deficit [Wullschleger, 2002]. Our study is specifically designed to investigate the impact of CO₂-driven physiological effects on extremes through changes in land-atmosphere interactions, here taking the 2003 European heat wave as a case study. Previous studies have not taken into account the impact of the surface CO₂ physiological effect on land-atmosphere interactions when studying regional extreme events (e.g. [Seneviratne *et al.*, 2006]). We use a Regional Climate Model (RCM) to investigate the physical mechanisms of land-atmosphere interactions, similarly to other authors [Seneviratne *et al.*, 2006; Stéfanon *et al.*, 2012]. We purposely do not use GCMs as, in addition to their coarse resolution and initialization issues, they only allow characterizing *statistical* changes of frequency and intensity of heat waves and droughts, and cannot directly quantify the relative contribution of each physical or physiological process on a specific weather event. In addition, GCMs have difficulties representing large-scale blocking conditions especially in the Euro-Atlantic region [D'Andrea *et al.*, 1998; Sillmann and Croci-Maspoli, 2009], and are

thus not ideal for investigating mid-latitude heat waves. Unlike GCMs, RCMs are aimed at understanding physical processes by repeating near-twin runs using the same large-scale forcing but with a different set of parameters or processes (see Methods and Table S1). For each run, we can estimate the contribution of the process and parameter under the same prescribed synoptic conditions [Seneviratne *et al.*, 2006].

2. Methods

2.1 Model setup

In this experiment the WRF (Weather and Research Forecasting - v.3.1.1) limited-area model is coupled with the ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems – v.1.9.5) land-surface model [Drobinski *et al.*, 2012]. WRF is an atmospheric model with non-hydrostatic core used for regional climate simulations [Skamarock *et al.*, 2008]. ERA-Interim reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) [Dee *et al.*, 2011] provides the initial and lateral weather conditions (temperature, wind and humidity). ORCHIDEE simulates the surface processes of the terrestrial biosphere – in particular the soil water budget and the photosynthesis – as well as the phenology and the carbon dynamics [Krinner *et al.*, 2005; Stéfanon *et al.*, 2012]. This coupled model setup has been shown to produce results consistent with observations of the 2003 heat wave [Stéfanon *et al.*, 2012]. A spin-up is first applied by repeating the year 2002 twice so that the leaf area index and soil moisture are in a dynamic equilibrium at the beginning of 2003.

The study focuses on the summer and especially the heat wave of 2003, which exhibited more than 4K temperature anomaly over Western Europe. This anomaly is similar in

amplitude to the expected temperature changes in 2100 under the Representative Concentration Pathway 8.5 scenario of the International Panel on Climate Change (IPCC) report – likely in the range of 2.4 to 4.8 K in the global mean, and from 4 to 8 K during the summer in Central Europe. Therefore, our setup gives insights on how the CO₂ physiological effects might affect surface fluxes and regional temperature patterns in a typical summer at the end of the century.

Two sets of simulations are performed on domains of different sizes. In the first set of simulations, the domain extends from 6.4°W to 10.4°E and from 41.5°N to 51.7°N, with a 0.26° grid cell. At this scale, the lateral boundary conditions control is substantial, so that there cannot be large-scale temperature deviations across simulations while still resolving the regional impact of land-atmosphere interaction changes. The second set of simulations is run on an extended domain from 10.5°W to 26.5°E and from 35°N to 59°N, with a 0.22° grid cell. On this larger domain, the influence of the boundary conditions becomes less important and larger-scale patterns can be altered. In other words, this larger domain tests the sensitivity of the results to the prescribed lateral boundary conditions and domain size. However, as is elaborated below, the main results and conclusions are not modified over the larger domain and confirm the findings of the smaller domain.

2.2 ORCHIDEE and the vegetation model

The surface model takes into account 12 different Plant Functional Types (PFTs). Agricultural C3 crop is the most frequent PFT throughout the domain, followed by C3 grass and temperate broad-leaved summer green plant (deciduous forests), covering similar areas. ORCHIDEE has been shown to produce results consistent with local flux tower data [*Anav et*

al., 2010] and LAI satellite observations [Lafont *et al.*, 2012]. ORCHIDEE has also been evaluated in the context of elevated CO₂ [Cheaib *et al.*, 2012] and has been successfully validated against multiple FACE datasets in a recent inter-model comparison study, where the LAI is however reported to be somewhat overestimated by ORCHIDEE [De Kauwe *et al.*, 2013; Walker *et al.*, 2014]. The version used here does not include the nutrient cycle. Table S2 points out to the other differences with the model used in De Kauwe *et al.* [2013].

2.3 Surface CO₂ and other Greenhouse gasses concentrations

Two types of simulations are performed (Table S1). The first is the control run or CTL, and the surface model is set with the observed mean CO₂ concentration of 2003 (376 ppm) while in the second one, FER, the surface model is set with the CO₂ concentration expected for 2100 in the RCP 8.5 (936 ppm) [Moss *et al.*, 2010]. In FER, the CO₂ concentration of the atmospheric model is not changed, enabling us to estimate the sole impact of CO₂ physiological effects on the surface vegetation, land-atmosphere interactions and heat wave. Another experiment was performed, named FER_{dry}, a replicate of the FER run but with soil moisture imposed to the CTL values, which are drier than in FER. By doing so, we separate the effect of seasonal CO₂-induced water saving on land-atmosphere feedbacks (Figure 1c) from the other effects - namely the CO₂ fertilization and the instantaneous stomatal response feedback (Figure 1a and b). The method to constrain the soil moisture level leads to a soil moisture difference between CTL and FER_{dry} of less than 0.6 kg/m² or <0.3% of the total amount, and 7% of the maximum difference between CTL and FER. This is due to the variety of PFT fractions of each pixel. We imposed the same average CTL value of the pixel to all

PFTs of the pixel, instead of generating the various soil moisture values for each PFT as in the original version of the code.

2.4 Sensitivity analysis with additional runs

A set of additional experiments has been run to test the sensitivity of the results to several critical model parameters. Each parameter is tested with both the CTL and FER surface CO₂ conditions. To test the sensitivity to phenology and LAI, the leaf onset is delayed by increasing the growing degree-day by 50% in ORCHIDEE (Figure S3 a, e). In a second set of experiments, the planetary boundary layer scheme used in WRF for the first experiment (the non-local, counter-gradient, Yonsei University scheme - YSU) is switched to another scheme (a local 2.5-order turbulent closure Mellor-Yamada-Nakanishi and Niino scheme - MYNN 2.5) (Figure S3 b, f). To test the sensitivity to the stomatal conductance parameterization, we modified the parameter representing the temperature dependence of photosynthesis (Figure S3 c, g) and the parameter representing the soil moisture stress in $V_{c_{max}}$, i.e., the maximum rate of Rubisco carboxylation (Figure S3 d, h). This way, we alter either the temperature stress response of the vegetation or its water use efficiency. In both cases, the original parameter value x (between 0 and 1) was modified for the sensitivity analysis to a higher value $x+(1-x)/2$. Table S1 summarizes the model parameters modified from the base case CTL for each simulation.

3. Results and discussion

3.1 Small domain

The small domain is centered over France, which experienced the peak of the 2003 heatwave. FER exhibits significantly less latent heat flux than CTL throughout the growing season (Figure 2b), as a direct consequence of the reduction of the stomatal conductance under higher CO₂ concentration (Figure 1a). As a result, FER displays increased soil moisture content compared to CTL (Figure 2a) consistently throughout the growing season (Figure 3a). The stomatal closure also translates into higher sensible heat flux (Figure 2d, 3h) and higher surface temperature (Figures 2c, 3c). However, the latent heat flux difference between FER and CTL is reduced from mid-March onward because of the larger LAI due to the CO₂ fertilization effect in FER (Figure 1b, S1a, S1b).

During the growing season, similarly to FER, lower latent heat fluxes (Figure 2b, S2d) and higher temperature than CTL are experienced (Figure 2c, S2c) in FER_{dry}. Latent heat flux in FER_{dry} and FER are of the same order of magnitude during the growing season. This is expected since the growing season difference is dominated by the CO₂ stomatal closure (Figure 1a), as soil water is not limiting early in the season. The daily maximum temperature, as well as the sensible heat flux, are also of the same order of magnitude in both FER and FER_{dry}. However, starting mid-March, due to lower LAI in FER_{dry} than in FER (Figure S1a, S1b), fluxes and temperature begin to progressively diverge, FER_{dry} showing less latent heat flux than FER, more sensible heat flux, and higher temperature.

In contrast to the growing season, during the June heat wave, stomatal closure is not the main driver of latent heat flux difference between FER and CTL anymore. The latent heat flux is indeed now higher in FER than in CTL (Figures 2b, 3f), which holds true for the rest of the summer. The higher LAI in FER could be one of the reasons explaining the increased latent

heat flux. LAI is indeed 37% larger in FER than in CTL during the summer (Figure S1). As a consequence of higher latent heat flux, the soil moisture in FER decreases compared to CTL (Figures 2a, 3e), and the spring soil moisture surplus is depleted to sustain higher transpiration (Figure 1c).

We can evaluate the differential impact of the soil moisture surplus on one side and the larger LAI on the other side comparing FER to FER_{dry}. The response to summertime temperatures in FER is unequivocal with more latent heat and less sensible heat fluxes than in CTL (Figure 3f and 3h). In contrast, the response is spatially different in FER_{dry} with latent and sensible heat fluxes close to the levels in CTL (Figure S2d and S2f).

The latent heat difference FER_{dry}-CTL averaged from 8 June to 16 August 2003 over the entire domain is about a quarter that of FER-CTL (Figure 2c). LAI in FER_{dry} is 22% higher than in CTL, but latent heat increases by only 4% (Figure S2d). LAI in FER is 37% higher than in CTL, and latent heat increases by 14% (Figure 3f). There may be a contribution of the CO₂ fertilization effect (Figure 1b) to the latent heat flux difference between FER_{dry} and FER during the summer, but the soil moisture saving induced by stomatal closure (Figure 1c) as assessed by (FER- FER_{dry}) accounts for the larger share. Figure 2 suggests, however, a less categorical conclusion for the most extreme periods of the summer, during which the heat fluxes in FER_{dry} are very different than in CTL, implying an important contribution of the LAI during this period.

The corresponding reduction in sensible heat flux (Figure 2d) translates into lower temperature, which is of great importance during the hottest part of the season. Nonetheless,

the model set-up with the constraint of prescribed temperature boundary conditions does not allow representing significant temperature differences between FER, FER_{dry} and CTL. Surface fluxes are allowed to evolve freely and are of comparable magnitude to typical global warming impact (e.g. Representative Concentration Pathway RCP 8.5 – with 8.5 W m⁻²). The prescribed temperature boundary condition is an obvious caveat of the adopted framework.

FACE experiments on crops and grass tend to show less pronounced fertilization than simulated by ORCHIDEE [Ainsworth and Long, 2005; De Kauwe et al., 2013]. If LAI were lower than simulated by the model (as in FACE), the water savings would be even larger during the growing season, and this water could further sustain transpiration in the summer, thus reducing water stress. This would reinforce our results and further amplify the mitigation of heat stress through increased soil moisture.

3.2 Sensitivity to model parameters

Given the uncertainties in the model parameterization and representation of the coupling between the carbon and water cycle, we performed a series of sensitivity studies to the different model parameters. The additional runs using different bud break date, planetary boundary layer scheme, and dependence of stomatal conductance to temperature and soil moisture (Methods) confirm the results highlighted above. The main result – that the CO₂-induced water savings mitigate the heat wave and summer dryness holds true for all these sensitivity experiments (Figure S3a to S3h), but with a different amplitude. The bud break day and the temperature dependence of the stomatal conductance do not have much influence on the results, but the dependence of stomatal conductance on soil moisture (i.e. the modeled

intrinsic water use efficiency) does, which further emphasizes that characterization of the carbon and water cycles coupling is key for accurate seasonal prediction of land-atmosphere interactions and of heat waves in particular. The boundary layer scheme is also important in modulating the impact of land-atmosphere interactions, especially during the heat wave period. Indeed during heatwaves, the unstable boundary layer experiences intense updrafts spanning the entire boundary layer depth and the nighttime boundary layer does not become stable [Miralles *et al.*, 2014]. It is therefore expected that a scheme (YSU) that better accounts for non-local turbulent transport and explicitly represents thermals would better model the heat-wave boundary layer. Entrainment and vertical mixing are the most significant differences among boundary layer schemes in WRF, which have considerable consequences on the intensity of the vertical mixing and fluxes [Hu *et al.*, 2010]. Nonetheless, only the FER_{dry} run radically affects the pattern of decreased latent heat flux during spring and increased latent heat flux – concurrently with temperature - during summer compared to CTL (Figure S3i and S3j).

3.3 Large domain

To test the dependence of the results on the domain size and to the prescribed lateral temperature boundary conditions we performed a second set of simulations (CTL, FER) over a larger domain covering continental Europe (Methods). As many regions of the extended domain did not experience temperatures as extreme as France [Seneviratne *et al.*, 2006] those simulations are also used to investigate the robustness of the findings to less extreme temperature anomalies and more typical summer conditions.

The water-saving feedback observed over the smaller domain similarly occurs over the extended domain (Figure S4). Over France, we observe the same range of magnitude for spring soil water savings and latent heat seasonal change. Evapotranspiration is stronger in FER than in CTL during the summer (Figure S4b and S4f), as reduced stomatal opening during the growing season has conserved water. Except in a few sea-dominated locations along the coasts (Iberian Peninsula, extreme south of Italy and south of Greece), the FER simulation exhibits lower surface average temperatures difference with CTL in the Summer compared to Spring over a significant part of the domain (Figure S4c and S4g). This lower temperature difference is due to the higher latent heat flux (Figure S4f) accompanied by a reduction of sensible heat flux (Figure S4h). In other words, the seasonal water cycle feedback and the larger LAI compensates for the stomatal response over this extended domain. These effects are particularly strong over central and Eastern Europe. This more continental part of Europe exhibits indeed strong land-atmosphere temperature coupling [Senoussi *et al.*, 2006], stronger than over France, and is less influenced by maritime air advection. In continental Europe, the spring stomatal water savings seem however not enough to overcome the transpiration stimulation by the larger LAI, and soil moisture content tends to decrease in FER compared to CTL in these regions even during spring.

4. Conclusion

The present study illustrates the role of plant physiology in altering land-atmosphere interactions under higher CO₂ concentration. CO₂ indirect effects can mitigate heat-wave impacts and the severity of summer dryness in the Western Europe mid-latitude climate.

Spring water savings enabled by increased ecosystem water use efficiency modifies the surface energy partitioning, allowing increased latent heat flux later in the summer that more than compensates the reduced stomatal opening induced by increased CO₂. Mitigation of extreme temperature anomalies is more pronounced in regions experiencing summer water stress and in regions of strong land-atmosphere coupling. We demonstrated that the characterization of the surface CO₂ physiological effects is essential to accurately predict seasonal climate and extremes. This has important implications for climate model prediction of continental heat waves and dryness. Future droughts and heat wave intensity might indeed be partially attenuated by the carbon-water feedback, and especially by the water use-efficiency. Such attenuation depends on the competing contributions of the fertilization and stomatal closure effects, which are biome and climate dependent. This calls for additional studies on the statistical changes in heat-wave characteristics induced by vegetation physiology using GCMs.

Other biogeochemical processes and nutrient feedbacks could also play an important role in the context of rising atmospheric CO₂, but these remain poorly represented in current generation models [Zaehle *et al.*, 2014]. Water stress regulation of photosynthesis neither is accurately represented in land-surface models nor accounts for the diversity of strategies observed from active (isohydric behavior) to minimal stomatal regulation (anisohydric behavior) under water stress [Mcdowell, 2011; Gentine *et al.*, 2016; Konings and Gentine, 2016].

In addition to highlighting the importance of the land-atmosphere interactions induced by CO₂ for future model improvements [Fatichi *et al.*, 2016], these findings have important implications for better estimating summertime heat waves in the context of projected future

warming or drying across much of Europe [*Seneviratne et al.*, 2006; *Giorgi and Lionello*, 2008; *Dai*, 2013], emphasizing the role of the plant water use efficiency and its model representation for extreme event prediction.

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Figure Captions

Figure 1. Dominant carbon, energy and water feedbacks. (a) During the growing season, the water use efficiency due to higher CO₂ concentrations reduces latent heat flux, increasing air temperature and soil moisture. (b) In early summer, the increase in LAI due to CO₂ fertilization increases the latent heat flux and leads to a temperature reduction. (c) During a heat wave, the spring soil moisture savings decrease the stress of the vegetation and increase the transpiration leading to a decrease of the peak temperature. Minus (positive) sign reads decrease (increase).

Figure 2. Effects of the water cycle feedback on temperature over the small domain. Left column shows averages over the domain of the main components of the water cycle (a) soil moisture (0-200 cm) (kg/m²) (b) latent heat flux at 15:00 UTC (W/m²). Right column shows averages over the domain of the (c) daily maximum temperature (K) and (d) sensible heat flux (W/m²) at 15:00 UTC. Data is shown for the period from 19 February (DOY 50) to 7 September 2003 (DOY 250). All variables are expressed as a difference relative to CTL of the two runs FER (blue) and FER_{dry} (red, dashed). Grey shaded areas correspond to the period where the temperature anomaly was above the 95th percentile in 2003, the periods of an extreme heat wave over the domain. The red and blue shaded areas correspond to respectively the FER_{dry}-FER and FER-CTL differences. Except for the soil moisture, the time series are smoothed by a 3-days running average.

Figure 3. Physiological effect (FER) over the small domain during spring and summer. The left column presents an average of the variables for FER expressed as the difference to

CTL for spring (15 March to 8 June 2003), while the right column displays the same results for the summer period (8 June to 16 August 2003). The presented variables are the average soil moisture content (kg/m^2) (**a, e**), the average latent heat flux (W/m^2) at 15:00 UTC (**b, f**), the daily max temperature (K) (**c, g**) and the average sensible heat flux (W/m^2) at 15:00 UTC (**d, h**)

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Data is available upon request by email to the lead author. The authors declare neither real or perceived conflict of interest nor competing interest.

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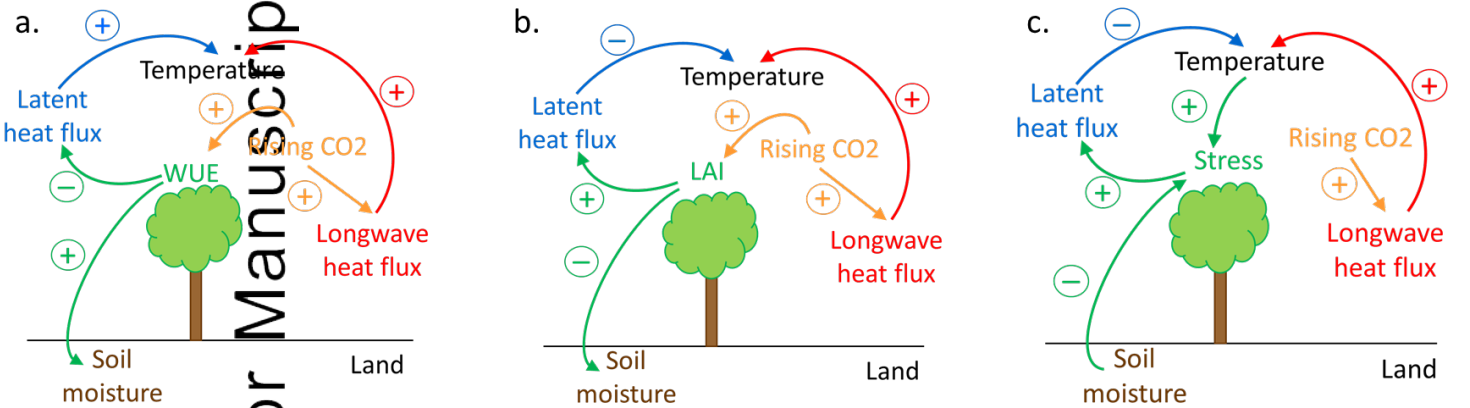
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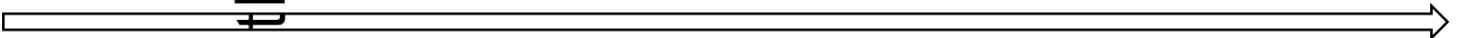
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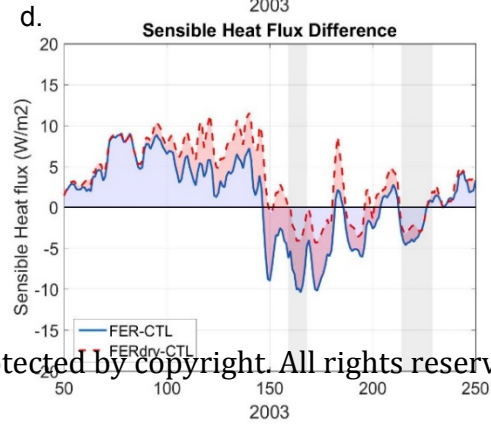
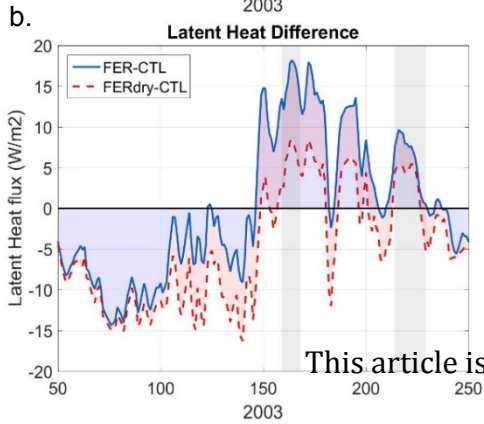
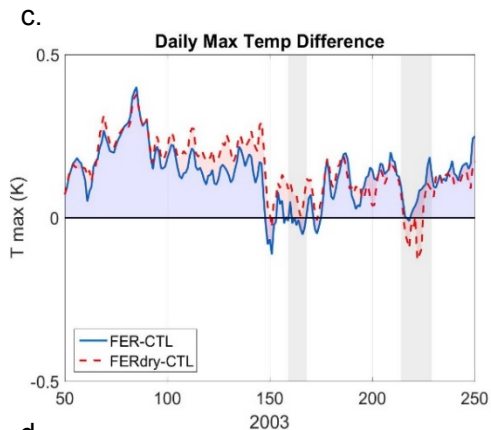
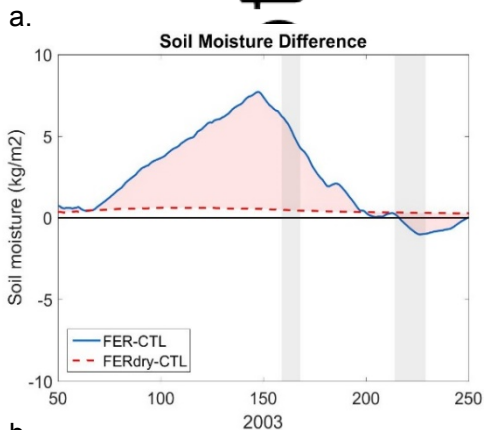


Growing season

Early Summer

Heat-wave

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