The Physiological Effect of CO₂ on the Hydrological Cycle in Summer over Europe and Land-Atmosphere Interactions.

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Abstract

Past studies have shown that the physiological effect of CO₂ may be important for future climate change, yet many regional climate models and hydrological models used in impact studies do not simulate it. Here, the role the physiological effect of CO₂ on the changes in the continental hydrological cycle over Europe in summer -when severe drying is projected- is assessed using a large ensemble of idealized climate simulations, and compared to the radiative impacts of CO₂. As expected, the physiological effect of CO₂ leads to a decrease in evapotranspiration. However, it generally does not lead to an increase in river flows or soil moisture as often expected, because it is also associated with a large decrease in precipitation. This decrease in precipitation is likely due to small warming and decrease in specific humidity caused by the physiologically driven decrease in evapotranspiration, which together leads to a large decrease in relative humidity. Important inter-model uncertainties however exist regarding the physiological impact of CO₂ on the summer hydrological cycle over Europe.

Keywords: Climate change; Europe; hydrological cycle; physiological effect of CO₂; land-atmosphere interactions

Declarations

Funding: Not applicable

Conflicts of interest/Competing interests: Not applicable

Availability of data and material: The CMIP6 data used in this study can be freely downloaded at <https://esgf-node.ipsl.upmc.fr/projects/cmip6-ipsi/>

Code availability: Not applicable

Ethical Approval: Not applicable

Consent to Participate: Not applicable

Consent to Publish: Not applicable

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36 **1. Introduction**

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38 Climate change will have severe impacts on the hydrological cycle over Europe. In particular,
39 severe drying is projected in summer over most of Europe south of Scandinavia (Collins et al.
40 2013), with potential far-reaching impacts in many domains, such as agriculture and energy.
41 Very large uncertainties however exist in projected hydro-climate changes over Europe, with
42 an important role of continental surfaces and land-atmosphere interactions in that context (e.g.
43 Seneviratne et al. 2006, Boé and Terray 2008).

44 Large discrepancies between current regional projections, from EURO-CORDEX (Jacob et al.
45 2014), and global climate projections, from the Coupled Model Intercomparison Project
46 Phase 5 (CMIP5, Taylor et al. 2012) have even been highlighted recently. Stronger warming,
47 stronger precipitation and evapotranspiration decreases are indeed projected by global climate
48 models (GCMs) compared to regional climate models (RCMs) over Europe in summer (Boé
49 et al. 2020). Different mechanisms have been shown to be important in that context. In
50 addition to the lack of time-varying aerosol forcing in most RCMs (Boé et al. 2020), the lack
51 of simulation of the physiological effect of CO₂ by RCMs, which is simulated by a majority
52 of CMIP5 GCMs, was suggested to be potentially important (Schwingshackl et al. 2019).

53

54 It has long been known that rising CO₂ concentration can impact climate change not simply
55 through the radiative effect of CO₂, but also through its physiological effect on vegetation
56 (e.g. Douville et al. 2000). Leaf stomata tend to close under higher atmospheric CO₂
57 concentration, reducing transpiration (Field et al. 1995, Franck et al. 2015). However,
58 increased CO₂ concentration may favor biomass production, increasing leaf area and therefore
59 transpiration (Strain 1987, Norby et al. 2011). The relative importance of these two effects is
60 likely time-scale dependent. For climate change in the 21st century, the former process is
61 generally expected to be dominant, resulting in an overall decrease in evapotranspiration due to
62 the physiological effect of CO₂ (e.g. Lemordant et al. 2018). This decrease in
63 evapotranspiration may lead to a warmer boundary layer, and to lower relative humidity and
64 precipitation, as shown by Andrews et al. (2011) based on a single climate model.

65 Consistently, recent studies have shown that the physiological effect of CO₂ could be
66 important, for example regarding the fast precipitation response to CO₂ forcing (DeAngelis et
67 al. 2016), changes in global temperature extremes (Skinner et al. 2018, Lemordant and

Gentine 2019), daily precipitation properties (Skinner et al. 2017), or the global hydrological cycle (Hong et al. 2019, Lemordant et al. 2018). In the latter study, a weak physiological impact of CO₂ on precipitation changes at the annual level in Europe is noted, with a weak increase in precipitation minus evapotranspiration, i.e. in runoff. This is consistent with Cao et al. (2010) who have shown an increase in runoff in many regions of the world due to the physiological impact of CO₂, based on a single climate model.

All these studies are generally based on very few climate models, or even sometimes a single climate model, and therefore it is still not clear how robust their results are, especially since large uncertainties in the simulation of the physiological impact of CO₂ may exist.

As noted by previous studies, the decrease in evapotranspiration due the physiological response of vegetation to CO₂ is expected to reduce the loss of water at surface in the future climate, and therefore to limit the decrease (amplify the increase) in river flows projected in some regions because of the radiative impact of CO₂ alone.

The lack of simulation of the physiological effect of CO₂ by some GCMs and the great majority of current RCMs over Europe (Schwingshackl et al. 2019) is therefore of concern in this context. Additionally, the impacts of climate change on the hydrological cycle are generally assessed through offline hydrological simulations. The hydrological models used are often conceptual and do not take into account the physiological effect of CO₂, which leads to large differences in changes in potential evapotranspiration compared to climate models that simulate this effect (Milly and Dunne 2016). The stomata-related physiological effect of CO₂ on potential evapotranspiration could be accounted for in a simplified manner in conceptual hydrological models (Yang et al. 2019), but this is very rarely done. The overestimation of the increase in potential evapotranspiration due to the lack of the physiological effect of CO₂ is expected to potentially lead to overestimated (underestimated) projected evapotranspiration increases (decreases), with in the end an overestimation (underestimation) of decreases (increases) in rivers flows (Milly and Dune 2017).

The main objectives of this study are to assess the respective roles of radiative and physiological effects of CO₂ in summer hydrological changes in Europe, when these changes are especially strong, and to evaluate the mechanisms at play. Idealized climate simulations from an ensemble of nine new generation climate models from the Coupled Models Intercomparison Project phase 6 (CMIP6, Eyring et al. 2016) are analyzed. This large ensemble compared to previous studies allows a robust assessment of uncertainties.

2. Data

Climate simulations with new generation climate models from CMIP6 (Eyring et al. 2016) are studied. 1pctCO₂ simulations ("ALL" in the following) from the Diagnostic, Evaluation and Characterization of Klima (DECK) set of experiments as well as 1pctCO₂-rad ("RAD") and 1pctCO₂-bgc ("BGC") experiments from the Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP, Jones et al. 2016) are studied. In the 1pctCO₂ simulations, the CO₂ concentration increases of 1% per year from the pre-industrial value of about 285 ppm. The 1pctCO₂-rad simulations follow the same experimental design, except only the radiative code of the Earth System Model (ESM) sees the evolution of CO₂ concentration. The biogeochemical component of the ESM sees a constant pre-industrial CO₂ concentration. Conversely, in the 1pctCO₂-bgc simulations, only the biogeochemical component of the ESM sees the increase in CO₂ concentration: the radiative component sees a constant pre-industrial concentration of CO₂. The other forcings (e.g. anthropogenic aerosols, land-use) are fixed at pre-industrial values in all simulations.

The CMIP6 ESMs with the 1pctCO₂, 1pctCO₂-rad, 1pctCO₂-bgc simulations and the necessary variables for this study are analyzed, for a total of 9 ESMs: CanESM5 (Swart et al. 2019, using the CLASS-CTEM land model (Verseghy, 2000; Arora and Boer, 2005, 2010)), CNRM-ESM2-1 (Séférian et al. 2019, using the ISBA-CTRIP land model (Decharme et al., 2019; Delire et al., 2019)), IPSL-CM6A-LR (Boucher et al. 2020, using the ORCHIDEE land model (Krinner et al., 2005)), MIROC-ES2L (Hajima et al. 2020, using the MATSIRO with VISIT-e land model (Ito and Oikawa 2002)), UKESM1-0-LL (Sellar et al. 2019, using the JULES-ES1.0 land model (Wiltshire et al., 2020)), ACCESS-ESM1-5 (Law et al. 2017, using the CABLE2.4 with CASA-CNP land model (Wang et al., 2010)), MPI-ESM1-2-LR (Mauritsen et al. 2019, using the JSBACH3.2 land model, (Roeckner et al. 2003; Reick et al. 2013, Hagemann and Stacke 2015)), NorESM2-LM (Seland et al., 2020, using the CLM5 land model (Lawrence et al. 2019)) and CMCC-ESM2 (based on the CMCC-CM2 model described in Cherchi et al. (2019), using the CLM4.5 land model (Oleson et al. 2013)). With the exception of CMCC-ESM2 and NorESM2-LM, all ESMs in this study therefore use different land surface models.

The representation of land and vegetation processes varies among the models studied in this work. A majority of models simulate explicitly the nitrogen cycle (ACCESS-ESM1-5, CMCC-ESM2, MIROC-ES2L, MPI-ESM1-2-LR, NorESM2-LM and UKESM1-0-LL). This

may be important for the physiological effect of CO₂ because of the potential limitation of photosynthesis due nitrogen availability. Some models (CNRM-ESM2-1, IPSL-CM6A-LR and CanESM5) include an ad-hoc parameterization of photosynthesis down-regulation as CO₂ concentration increases. MPI-ESM1-2-LR and UKESM1-0-LL simulate a dynamic vegetation cover, which may impact their response to CO₂. CMCC-ESM2, CNRM-ESM2-1, MPI-ESM1-2-LR and NorESM2-LM have a fire parameterization. The number of plant functional types, dead and live carbon pools vary among the models. Further details can be found in Arora et al. (2020) and in the references for the ESMs and their land component given previously.

The representation of hydrological processes also varies among models. In particular, the CNRM-ESM2-1 model includes a flooding scheme with a representation of foodplains and a two-dimensional groundwater scheme to represent unconfined aquifers and upward capillarity fluxes into the superficial soil (Decharme et al. 2019), with potential impacts on evapotranspiration.

To characterize the impacts of increased CO₂ concentration, climatological averages on years 110-140 and years 1-31 are contrasted for most analyses in this study. On years 110-140, the CO₂ concentration is about 3.5 times the pre-industrial value, and close to 1000 ppm. The models are first interpolated on a common 1.5°x1.5° grid, with a patch algorithm (from the NCAR Command Language 2019). For all the spatial averages shown thereafter, only land points (defined as grid points with a land sea fraction greater than 75%) are selected before interpolation. For the maps, the mask is applied for the interpolation of only some of the variables (as visible in the figures). In the rare cases where several members are available, the ensemble mean is computed.

3. Changes in the continental hydrological cycle

The physiological and radiative impacts of CO₂ on evapotranspiration and precipitation changes are first compared. In ALL, summer evapotranspiration decreases over most of Europe except Scandinavia, where it increases, and the Alps, where evapotranspiration changes are close to zero. The strongest decreases are projected in southern Europe (Figure 1a). The pattern of evapotranspiration changes is quite similar in RAD, although with a stronger increase over Scandinavia, and also increases in the Alps and the northern part of eastern Europe, which are not seen in ALL. The decreases in France, central and eastern Europe are also often less severe in RAD. This is consistent with the evapotranspiration

response in BGC, which consists in a quasi-general decrease in Europe, more pronounced in an intermediate region between Scandinavia and southern Europe (Figure 1e).

In ALL and RAD, precipitation decreases everywhere over Europe except Scandinavia, with the largest decreases seen in France and the north of the Iberian Peninsula (Figure 1b and 1d).

A strong precipitation response is also noted in BGC (Figure 1f). The physiological effect of CO₂ generally leads to a decrease in precipitation, especially large in the same region where a strong decrease in evapotranspiration due to the physiological effect of CO₂ is also noted (e.g. France, Germany, Poland). Changes in the main continental hydrological variables over this region (red box in Figure 1f) are now studied.

The multi-model mean of spatially averaged evapotranspiration decreases both in ALL, RAD, and BGC (Figure 2a). However, the inter-model spread is large, and two models even simulate an increase in evapotranspiration in ALL and RAD. This is not surprising, as the response of evapotranspiration to climate change in the transition zone between Scandinavia and southern Europe is known to be highly uncertain in climate models, due to an important extent to large inter-model differences in the simulation of soil-atmosphere interactions (Boé and Terray 2008). For the models as an ensemble, the physiological impact of CO₂ on evapotranspiration is even greater than the radiative impact (BGC versus RAD, Figure 2a).

Precipitation decreases in all models and experiments (Figure 2b). The physiological effect of CO₂ on precipitation is also strong, even if it generally remains slightly weaker than the radiative effect.

The radiative and physiological effects of CO₂ are clearly not additive for both precipitation and evapotranspiration. The changes in ALL are indeed generally much smaller than the sum of the changes in BGC and RAD. This non-additivity is likely related to an important extent to the many potential non-linearities that exist in land-atmosphere interactions. An obvious example is that the additional physiological effect of CO₂ on evapotranspiration is expected to be weak under conditions where evapotranspiration is already very low due to the radiative impact of CO₂, when it leads to dry soils.

Evapotranspiration and precipitation changes, and their inter-model spread, are still noticeably smaller when only the radiative effect of CO₂ is simulated (RAD versus ALL), showing the importance of considering the physiological impact of CO₂ when dealing with hydro-climate changes in Europe. These results are consistent with the idea that the lack of simulation of the physiological effect of CO₂ in most of the current EURO-CORDEX RCMs is partly

responsible for the less severe changes in evapotranspiration and precipitation that they project compared to CMIP5 climate models (Boé et al. 2020, Schwingshackl et al. 2019).

Over the area of interest, the physiological impact of CO₂ on precipitation is often as strong, and sometimes even slightly stronger, than on evapotranspiration (Figure 3). The decrease in precipitation is indeed larger than the decrease in evapotranspiration in BGC for about half of the models (Figure 3). Note that a strong inter-model relationship exists between the physiological impact of CO₂ on evapotranspiration and its impact on precipitation (Figure 3), likely due to the strong two-way interactions that link precipitation and evapotranspiration changes. Precipitation changes impact evapotranspiration through the modulation of soil moisture. Conversely, soil moisture-precipitation feedbacks (e.g. Seneviratne et al. 2010) show how evapotranspiration changes may impact precipitation (see next section).

As a result of the relationship between evapotranspiration and precipitation changes, little changes in precipitation minus evapotranspiration (not shown) and water availability at surface generally occur in BGC. Only small ensemble mean changes in runoff and soil moisture are noted in BGC (Figure 2). Runoff even slightly decreases in BGC. Furthermore, the decrease in runoff in ALL is slightly greater than in RAD.

Because of soil-moisture memory, changes in soil moisture in summer can be influenced by previous changes in winter and spring. In winter and spring, the physiological impact of CO₂ on both evapotranspiration and precipitation is generally weak, and small changes in soil moisture (and runoff) are noted in BGC (Figure 4). Physiologically-driven changes in soil moisture in winter and spring therefore do not generally have a strong impact on changes in summer, when considering the ensemble mean.

Contrary to what is generally expected, over much of Europe in summer, the physiological effect of CO₂ does not lead to less severe decreases in runoff and soil moisture. Even if, as expected, evapotranspiration decreases, the physiological effect of CO₂ in the region also leads to a strong decrease in precipitation, which, from a surface water budget perspective, offsets the decrease in evapotranspiration. In some models, the decrease in precipitation is even larger than the decrease in evapotranspiration, resulting in a decrease in runoff.

In order to better isolate the signals associated with the physiological effect of CO₂, the previous analyses (and the ones in the next section) are performed for a large increase in CO₂ concentration (from about 285 ppm to 1000 ppm). However, if the future trajectory of CO₂ concentration is compatible with the 2015 Paris agreement's goal (i.e. to limit global warming to 1.5°C or 2°C), such a large increase in CO₂ concentration will not occur. This raises the question of whether for an increase in CO₂ concentration closer to that needed to meet the 2015 Paris Agreement target, the relevance of the physiological impact of CO₂ regarding hydrological changes remains. Thus, Figure 5 shows the same analysis as Figure 2, but between years 50-80 and years 1-31, a period with a mean CO₂ concentration close to 550 ppm, a value chosen based on Betts and McNeall (2018).

Changes in the hydrological cycle related to the radiative and physiological effect of CO₂ are obviously smaller than those previously shown for higher CO₂ concentrations in Figure 2, but the same basic features remain (Figure 5). A strong physiological impact of CO₂ is seen on evapotranspiration, stronger than the radiative one, and it also leads to a decrease in precipitation. In the end, a small decrease in runoff is also generally associated with the physiological impact of CO₂ at 550 ppm (Figure 5).

4. Mechanisms

The physiological effect of CO₂ does not generally lead to a less severe decrease in summer runoff in Europe, because it leads to a large decrease in precipitation, sometimes even greater than the associated decrease in evapotranspiration. It is therefore important to understand how precipitation is impacted by the physiological effect of CO₂.

Soil moisture-precipitation feedbacks (e.g. Seneviratne et al. 2010) illustrate how evapotranspiration anomalies, driven by soil moisture anomalies, may lead to precipitation anomalies. The same mechanisms are indeed likely to play, independently on whether the initial evapotranspiration anomalies are caused by the physiological impact of CO₂ or by soil moisture anomalies.

In regions where a large part of local precipitation comes from local evapotranspiration, a decrease in evapotranspiration may lead to a decrease in precipitation (Entekhabi et al. 1992).

This direct soil-moisture precipitation feedback, associated with recycling, is however not expected to be dominant in summer over Europe, where the indirect feedback is prevalent (Schär et al. 1999; Hohenegger et al. 2009, Leutwyler et al. 2021). Evapotranspiration anomalies may induce changes in boundary layer characteristics and/or atmospheric stability, which ultimately lead to precipitation anomalies (Schär et al. 1999; Hohenegger et al. 2009; Leutwyler et al. 2021). In this section, the mechanisms responsible for the physiological effect of CO₂ on precipitation are investigated.

The ensemble mean temperature in BGC slightly increases (1 K). This is much smaller than the 6 K warming seen in ALL and the 5.5 K in RAD (Figure 6a), pointing to a rather small impact of physiological CO₂ effect on warming.

The decrease in evapotranspiration noted earlier in BGC (Figure 2a) leads to a decrease in specific humidity at 2m (Figure 6b). This is not the case in RAD. The strong ocean warming in RAD leads to an increase in ocean evapotranspiration, atmospheric moisture advection over Europe (not shown) and in the end to a large increase in specific humidity there, despite the local reduction of land evapotranspiration.

Although small, the warming in BGC together with the decrease in specific humidity leads to a strong decrease in relative humidity (Figure 6c). It is almost as large as the decrease in relative humidity also seen in RAD, which in that case is due to an increase in actual humidity smaller than the increase in atmospheric water holding capacity caused by the large warming over land.

The decrease in relative humidity is also likely responsible to an important extent for the substantial increase in shortwave radiation at surface noted in BGC (Figure 6d), through a induced decrease in cloud cover (Figure 6e). Together with the reduction in evapotranspiration, this increase in solar radiation explains the surface warming noted in BGC. Note that the increase in LAI in BGC (Figure 9d) may also impact the surface albedo, and therefore temperature.

The decrease in relative humidity near the surface in BGC (and RAD) is expected to lead to an increase in the lifting condensation level (LCL). The LCL represents the height to which an air parcel has to be lifted in order to become saturated, and therefore for clouds and/or precipitation to form (Wei et al. 2021). The LCL is therefore an interesting indicator of likelihood of precipitation, and has been shown to be important in soil moisture-precipitation feedback (Betts 2009, Boé 2013). The LCL is approximately proportional to the difference

between temperature and dew point temperature (Lawrence, 2015) and therefore strongly influenced by relative humidity.

The LCL, calculated following the simplified formula given by Lawrence (2015), largely increases in ALL, BGC and RAD (Figure 6f). The increase in LCL in BGC is large, almost as large as the one seen in RAD. As the lifting condensation level rises, it becomes more difficult to reach, which favors a decrease in precipitation.

Changes in atmospheric stability, and therefore in vertical temperature and humidity profiles, may also be important regarding the impact of evapotranspiration on precipitation (e.g. Leutwyler et al. 2021). The physiological and radiative impacts of CO₂ on the vertical profile of temperature are very different, and not only in terms of intensity (Figure 7). While the warming associated with the radiative effect of CO₂ is seen in the entire troposphere and tends to be greater in the upper troposphere, the temperature anomalies associated with the physiological effect of CO₂ are limited to the lower troposphere, and lie below 700 hPa. This is not surprising as the warming due to the physiological effect of CO₂ is related to a decrease in evaporative cooling and an increase in solar radiation at surface, as discussed previously. Changes in the vertical profiles of relative humidity are also different in BGC and RAD, with a decrease in the whole troposphere in RAD and only in the lower troposphere in BGC. Still, the decrease in relative humidity in BGC is not limited to the near surface and reaches 700 hPa.

The decrease in relative humidity in the lower troposphere due to the physiological impact of CO₂ is expected to lead to an overall increase in stability, while the warming profile in BGC tends to decrease atmospheric stability. The physiological effect of CO₂ might therefore impact precipitation changes through a modulation of atmospheric stability, but the direction of this impact is not clear from the analyses discussed here. A much more detailed analysis, event-focused, based on higher vertical resolution outputs at higher temporal frequencies (i.e. at daily or, better, sub-daily time step) would be needed to characterize the role of stability in the changes in precipitation associated with the physiological impact of CO₂. The large majority of models do not provide such outputs for the simulations studied in this work.

Changes in large-scale atmospheric circulation have an important impact on changes in precipitation in northwestern Europe in summer (Boé et al. 2009). One may therefore wonder whether the physiological impact of CO₂ could be responsible for changes in atmospheric circulation leading to changes in precipitation. Figure 8 depicts the changes in summer large

scale circulation in ALL, RAD, and BGC. The pattern of sea level pressure and 500 hPa geopotential height changes are very similar in ALL and RAD, with positive surface pressure anomalies centered east of Ireland and a ridge aloft (Figure 8). These changes in atmospheric circulation likely contribute to the decrease in precipitation projected in the northern half of western Europe seen in ALL and RAD (Boé et al. 2009). Pressure and geopotential height anomalies in BGC tend to be spatially correlated with the anomalies simulated in ALL and RAD, but their intensity is very small, much smaller than the intensity of anomalies in ALL and RAD, especially for 500 hPa geopotential height. Changes in large-scale circulation therefore play only a very limited role in the hydro-climate changes associated with the physiological impact of CO₂ in summer over Europe.

The physiological effect of CO₂ on precipitation and evapotranspiration shows large spatial variations over Europe (Figure 1). It is now investigated why it is especially strong over an intermediate region between Scandinavia and southern Europe.

The physiological effect of CO₂ on temperature is greater on the same intermediate region between Scandinavia and southern Europe, with a maximum over eastern Europe where temperature anomalies are close to 1 K (Figure 9a). The spatial pattern of the physiological effect of CO₂ on specific and relative humidity (Figure 9b and 9c) is similar, with also smaller changes over the north and south of Europe, and larger changes seen over an intermediate area from France and the Baltic region. This pattern is similar to the one of the changes in precipitation and evapotranspiration in BGC noted earlier in Figure 1, suggesting that land-atmosphere interactions largely explain the spatial variations of the physiological effect of CO₂ on precipitation. The question is therefore now to understand the pattern of evapotranspiration changes in BGC, the first step of the land-atmosphere interactions described previously.

One may wonder whether changes in Leaf Area Index (LAI) could explain the spatial variations in evapotranspiration changes. As discussed in introduction, the physiological effect of CO₂ includes two opposite effects. In the one hand, CO₂ reduces stomata openings and therefore evapotranspiration but in the other hand it may favor an increase in biomass, and therefore in LAI and evapotranspiration. The spatial pattern of the changes in LAI in BGC, however, cannot explain the spatial pattern of evapotranspiration changes. Indeed, larger decreases in evapotranspiration are not necessarily seen where LAI increases less and conversely (Figure 9d).

Note that changes in meteorological variables driven by the radiative effect of CO₂ may also impact LAI. A strong signal in LAI is indeed noted in RAD (Figure 9e), with in particular a decrease in southern Europe, likely due to the strong drying and warming projected there. This decrease in LAI is expected to be responsible for an additional decrease in evapotranspiration, therefore potentially acting as a feedback regarding water loss at surface and temperature changes in RAD and ALL.

In the end, the spatial pattern of evapotranspiration changes in BGC is likely explained to a large extent by the climatological value of evapotranspiration (Figure 9f). The physiological effect of CO₂ is indeed necessarily limited where there is little vegetation in the first place, and where the climatological evapotranspiration is small. Consistently, evapotranspiration in BGC tends to decrease more where it is climatologically large, i.e. in an intermediate area between Scandinavia and southern Europe (Figure 9f), where the strong physiological impact of CO₂ on climate is also noted. Climatological evapotranspiration is especially large in this region because neither soil moisture (as in southern Europe) nor energy at surface (as in northern Europe) is a strong limiting factor of climatological summer evapotranspiration there (Boé et al. 2008).

These results are confirmed when the entire mid-latitudes of the Northern Hemisphere are considered. Indeed, the spatial patterns of multi-model mean precipitation and evapotranspiration changes in BGC are well correlated over this larger area (Figure 10a). Additionally, the changes in evapotranspiration are well spatially correlated with the climatological map of evapotranspiration (Figure 10b), although the relationship is not linear.

5. Discussion and conclusions

The physiological effect of CO₂ on summer evapotranspiration over Europe is strong, even potentially stronger than the radiative one over a large intermediate area between the north of Spain and the south of Scandinavia. However, over most of Europe the decrease in summer evapotranspiration due to the physiological effect of CO₂ is generally not associated with an increase in runoff, which would moderate the decrease due to the radiative effect of CO₂. This is because a strong decrease in precipitation, generally as large as the decrease in evapotranspiration, is also caused by the physiological effect of CO₂.

Previous studies such as Lemordant et al. (2018), focused on annual changes, have suggested a small positive physiological impact of CO₂ on runoff over Europe. This is not inconsistent with the present work, which deals with summer changes. In summer, the physiological impact of CO₂ on precipitation is especially strong, sometimes even stronger than the impact on evapotranspiration.

The decrease in precipitation due to the physiological effect of CO₂, crucial for the surface runoff response, is likely due to processes generally involved in land-atmosphere interactions. In particular, the decrease in evapotranspiration due to the physiological effect of CO₂ leads to a small decrease in specific humidity and a small increase in temperature, which combined effects lead to a large decrease in relative humidity, to a large increase in the lifting condensation level and consequently to a decrease in precipitation. This also leads to a decrease in cloud cover and to an increase in solar radiation at surface, which reinforces the initial surface warming due to reduced evapotranspiration. The physiological effect of CO₂ on summer evapotranspiration changes is particularly strong where climatological evapotranspiration is large. Note that the physiological and radiative effects of CO₂ are generally far from additive in summer over Europe, so the attribution of climate changes, in simulations including both effects, to one or the other is not unequivocal.

The physiological effect of CO₂ is important for summer hydro-climate changes in Europe, and the absence of this process in some global climate models and many current regional models could lead to underestimated warming and precipitation decreases, as well as to an underestimation of inter-model uncertainties. In our study, the inter-model spread in evapotranspiration, precipitation and temperature changes is larger in the simulations with both the radiative and physiological impacts of CO₂ compared to the simulations with only the radiative impact. The large inter-model uncertainties show that further progress in simulating the physiological effect of CO₂ is needed.

The idealized simulations analyzed in this study are only forced by CO₂. In reality, other forcings will evolve, and some of them, in particular anthropogenic aerosols, may have an important impact on summer hydro-climate changes in Europe (Boé 2016). More work is therefore needed to assess the impact of the physiological impact of CO₂ in the presence of other external forcings.

Most offline conceptual (and many non conceptual) hydrological models used to study the hydrological impacts of climate change do not take into account the physiological effect of CO₂ and therefore do not simulate the reduction in potential evapotranspiration associated with it, which is problematic (e.g. Milly and Dunne 2016, Milly and Dunne 2017). The present study suggests that this issue may be even more important when results from climate models that take into account the physiological impact of CO₂ are used as forcing. Indeed, the CO₂ physiological effect leads to a larger decrease in precipitation, which should be compensated to some extent for the surface water budget by the decrease in evapotranspiration also caused by the physiological effect of CO₂. This compensation obviously cannot occur with hydrological models that do not simulate it.

Note also that climate models with a strong physiological effect of CO₂ on evapotranspiration tend to also have a strong physiological effect of CO₂ on precipitation (Figure 3), with therefore a compensation with respect to changes in runoff and soil moisture. This suggests that inconsistencies between the strength of the physiological effect of CO₂ in an offline hydrological model that would simulate it (with respect to evapotranspiration) and in the climate model whose projections are used as forcing (with respect to precipitation) are likely to result in biases in projections of future river flows and soil moisture.

The strong coupling that exists between surface hydrology, vegetation and the atmosphere could therefore potentially challenge the use of offline hydrological modeling to project the impact of climate change on the continental hydrological cycle, and in particular on river flows. Earth System Models could become a valuable complementary tool in that context, but advances in resolution to achieve better runoff routing, in the representation of hydrological processes (e.g., aquifers are currently represented in very few models), and in the reduction of climate biases, are needed in this context.

Acknowledgments

The analyses and figures in this study have been done with the NCAR Command Language (Version 6.6.2) [Software]. (2019). Boulder, Colorado: UCAR/NCAR/CISL/TDD. <http://dx.doi.org/10.5065/D6WD3XH5>.

We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System

Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF.

Fig 1. Multi-model ensemble mean changes in JJA (a,c,e) evapotranspiration and (b,d,f) precipitation (mm/day) between years 110-140 and years 1-31 in (a,b) 1pctCO₂, (c,d) 1pctCO₂-rad, (e,f) 1pctCO₂-bgc simulations. The red box in f shows the region used to compute all the spatial averages in this study.

Fig. 2 Changes in the main variables of the continental hydrological cycle averaged over land between 42°N/58°N and -5°E /30°E (red box in Figure 1f) between years 110-140 and years 1-31 during summer (JJA) in (gray) ALL, (green) BGC, and (red) RAD for (a) evapotranspiration (mm/day), (b) precipitation (mm/day), (c) total runoff (mm/day) and (d) standardized total soil moisture (no unit). The mean and standard deviation of total soil moisture computed on years 1-31 from the ALL simulations are used for standardization in all cases. The boxes show the multi-model ensemble mean ± 1.64 multi-model standard deviation. The symbols show the results for the individual models: (plus) CanESM5, (asterisk) CNRM-ESM2-1, (circle) IPSL-CM6A-LR, (cross) MIROC-ES2L, (square) UKESM1-0-LL, (up triangle) ACCESS-ESM1-5, (down triangle) MPI-ESM1-2-LR, (diamond) NorESM2-LR, (left filled triangle) CMCC-ESM2.

Fig. 3 Changes in precipitation (y-axis, mm/day) versus changes in evapotranspiration (x-axis, mm/day), averaged over land between 42°N/58°N and -5°E /30°E (red box in Figure 1f) between years 110-140 and years 1-31 during summer (JJA) in BGC. Each point corresponds to a climate model. The dashed line is the y=x line.

Fig. 4 Same as Fig. 2 for winter and spring (DJFMAM)

Fig. 5 Same as Fig 2, but for changes between years 50-80 and years 1-31

546

547 **Fig. 6** Changes averaged over land between 42°N/58°N and -5°E/30°E (red box in
548 Figure 1f) during summer (JJA) between years 110-140 and years 1-31 in (a)
549 temperature at 2m (K), (b) specific humidity at 2m (g/kg), (c) relative humidity at 2m
550 (%), (d) downwelling shortwave radiation at surface ($W.m^{-2}$) (e) cloud cover (%) and (f)
551 the lifting condensation level computed at 2m, in (gray) ALL, (green) BGC, (red) RAD.
552 The boxes show the multi-model ensemble mean +/- 1.64 multi-model standard
553 deviation. The symbols show the results for the individual models (see legend in Figure
554 2). ACCESS-ESM1-5 is not available for cloud cover and NorESM2-LM is not available for
555 relative humidity and LCL.

Fig. 7 Vertical profile of changes in (a) temperature and (b) relative humidity averaged over land between 42°N/58°N and -5°E/30°E (red box in Figure 1f) during summer (JJA) between years 110-140 and years 1-31 in (gray) ALL, (green) BGC, (red) RAD. The lines show the multi-model ensemble mean and the shaded areas show the multi-model ensemble mean +/- 1.64 multi-model standard deviation. NorESM2-LM is not used in this figure.

Fig. 8 Multi-model ensemble mean changes in JJA between years 110-140 and years 1-31 of sea level pressure (hPa) in (a) ALL, (b) RAD and (c) BGC and in the 500 hPa geopotential height (m) in (d) ALL, (e) RAD and (f) BGC.

Fig. 9 Multi-model ensemble mean changes in JJA between years 110-140 and years 1-31 of (a) surface temperature in BGC (K), (b) specific humidity at surface (g/kg) in BGC, (c) relative humidity at surface in BGC (%), (d) LAI (no unit) in BGC, (e) LAI (no unit) in RAD. (f) Climatological evapotranspiration on years 1-31 (mm/day) in BGC. NorESM2-LM is not available for relative humidity.

Fig. 10: (a) Multi-model mean changes in summer precipitation (y-axis, mmd/day) versus changes in evapotranspiration (x-axis) in BGC in the Mid-Latitudes of the Northern Hemisphere (35°N – 80°N) over land. Each point corresponds to a continental grid point. (b) Multi-model mean changes in summer evapotranspiration (y-axis, mm/day) versus climatological evapotranspiration on year 1-31 (x-axis, mm/day) in BGC in the Mid-Latitudes of the Northern Hemisphere (35°N – 80°N) over land. Each point corresponds to a continental grid point. The spatial correlations are given in the titles of the sub-figures.

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