We are thankful to all reviewers for their valuable feedback which helped us to improve the manuscript. In response, aside from several minor corrections, we have introduced the following main changes to the paper:

- We have increased the amount of models considered in this study from 8 to 12.
- The ELI is now calculated with the soil moisture averaged over the top meter, which better represents effective water availability for terrestrial evaporation, as opposed to total column soil moisture.
- Hot spot region “NAS” has been moved northwards slightly and extended eastwards, as the regional pattern of largest changes in temperature excess has shifted slightly following the inclusion of additional models in the analysis.

As a result of these changes, the figures and main conclusions are even more pronounced or remain similar, which reflects the robustness of the methodology.

Using CMIP6 model projections, Denissen et al evaluate the co-occurrence of increasing trends in extreme temperature and increasing trends in ELI, a water-limitation metric. They find that these trends co-occur in many regions of the world especially in transitional and more energy limited regions. Therefore, more energy-limited locations are becoming more water-limited and experiencing more temperature extremes. This study is well done, carefully written, and concise which is always appreciated. I advocate for the use of ELI here which captures soil moisture and its nonlinear relation to energy fluxes. I find ELI to be a more direct variable to evaluate the questions here than soil moisture alone – something the authors could highlight more because it is a big strength compared to previous work.

My main criticism is the removal of many dryland regions, which I think are important for the message. I study the water, carbon, and energy cycles of these dry regions, including the influence of vegetation on the surface energy balance (for example, https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.16455; no expectation to cite). I am concerned that many of these regions are not fully included in the study and could bias overarching conclusions since they can respond so differently (see my #1 comment below). Nevertheless, I think it is a great study and ask the authors to consider several points.

-Andrew Feldman

Main Comments

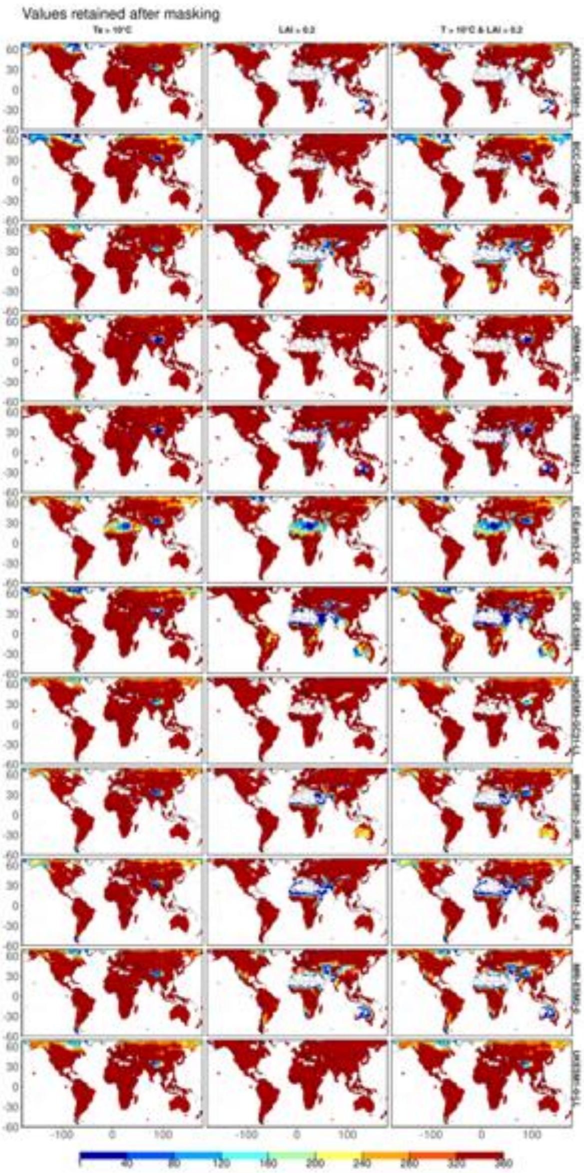
1) I find the condition in L114-115 to remove pixels at <0.5 m2/m2 of LAI is quite restrictive and removes many drylands, including the Sahel, most of China, and nearly all of Australia. These are key water limited regions to remove, especially in the context of heatwaves where these regions may be most vulnerable. Drylands have been deemed an important part of the climate system. Dryland vegetation also plays a critical role in the surface energy balance. See some studies here (with no expectation to cite) where meaningful dryland vegetation energy balance studies were conducted with different results from expectations:

https://www.science.org/doi/10.1126/science.abm9684 https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.16455

I suggest using a less restrictive condition. Or be very clear motivating why such a strict condition is used here to remove these dry places.

Thanks - we agree with this argumentation. In response we have made the LAI threshold less restrictive, filtering grid cells that have a monthly LAI lower than 0.2. Therefore, but also because we use more and a different set of CMIP6 models, we retain more dryland regions in the Sahel and in Australia. This is addressed in the following lines in the methodology

"Second, to additionally assure that we are investigating the active vegetation periods during the warm season, which would elicit vegetation responses to anomalies in energy and water supply affecting the surface flux partitioning, all months with Ta < 10˚C and Leaf Area Index (LAI) < 0.2 m2 m-2 are excluded from the analysis. Thereby, we disregard mainly grid cells in the most sparsely vegetated regions in Northern Africa and Western China and cold regions in the Northern latitudes, but retain major drylands including parts of the Sahel and the Australian interior (Supplementary Figure 2)."



Supplementary Figure 2: *Data points retained after masking. Columns denote the applied filtering procedures (from left to right: Ta < 10˚C, LAI < 0.5 and Ta < 10˚C & LAI < 0.5). Rows reflect the different individual models. The colors show the amount of values retained after filtering, where the maximum amount of values possible equals 3 hottest months per year over 120 years (360 data points). No data is available in the white regions.*

These water-limited dryland regions play an important role in temperature excess trends, as sensitivity of temperature excess trends to ELI in such regions is the highest (Figure 5d). We clarify this in the following lines in the abstract, the results and the conclusion.

"Sensitivity of temperature excess trends to ELI trends is highest in water-limited regions, such that in these regions relatively small ELI trends can amount to drastic temperature excess trends."

"Moving beyond trends we also analyze the sensitivity of decadal temperature excess with respect to ELI for energy-limited vs. transitional vs. water-limited areas and find the strongest relationship in the case of water-limited areas (Figure 5d), as evidenced by the largest increase in temperature excess with ELI. This confirms that changes in water-limited areas temperature excess trends are most sensitive to ELI trends. This stresses that evaporative cooling in already arid drylands is even further reduced, increasingly limiting their ability to mitigate future heat extremes (Feldman et al., 2023).“

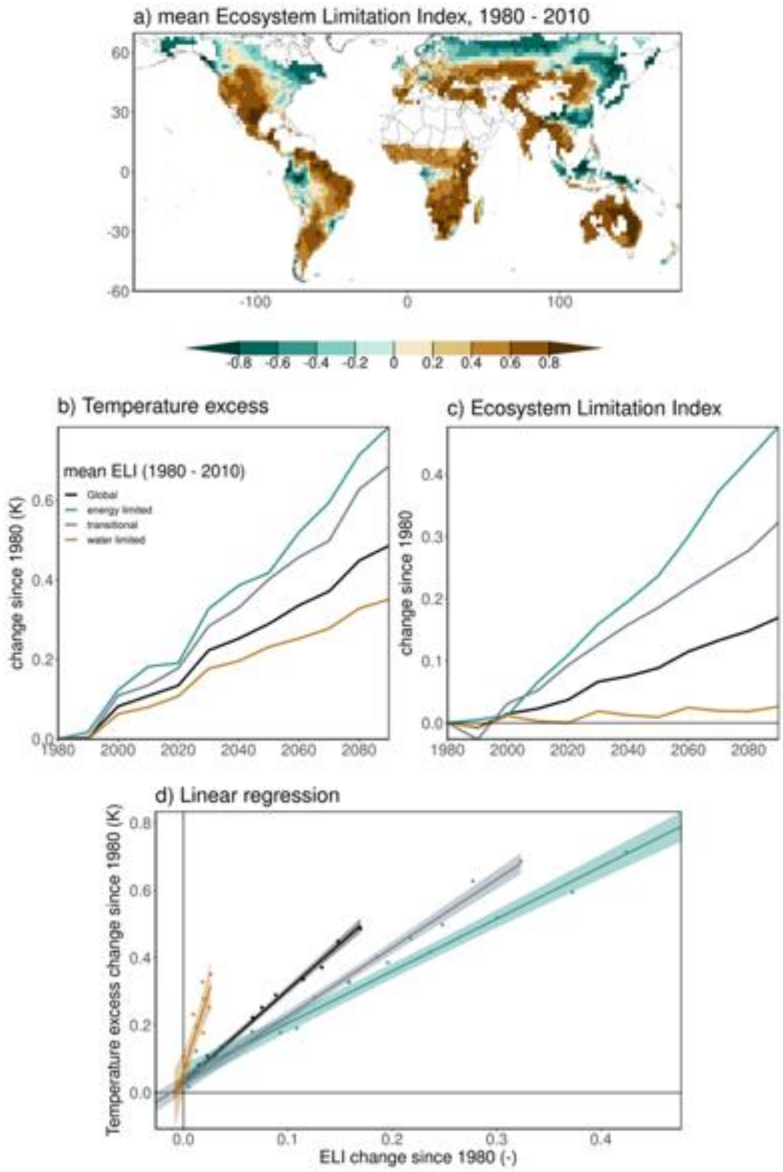


Figure 5. *Relation between temperature excess and ecosystem water limitation. a) Multi-model mean Ecosystem Limitation Index (1980 - 2010). Solid lines depict the time series of multi-model means inferred from globally (black) and regionally (colored) decadally averaged model simulations for b) temperature excess and c) Ecosystem Limitation Index. The classification is defined based on the model-specific mean ELI over 1980 - 2010 (Supplementary Figure 9): Energy limited (ELI < -0.2), transitional (-0.2 < ELI < 0.2) and water limited (ELI > 0.2). d) Points denote the global (black) and regional (colored) decadal multi-model means of ELI (x-axis) and temperature excess (y-axis), expressed as change since 1980. The lines denote linear regressions, with a shaded colored 95% confidence interval. Land grid cells that do not have complete time series for all models are excluded (white regions, Methods). Global and regional averages are weighted according to the surface area per grid cell.*

“Thereby, the relevance of trends in ecosystem water limitation for trends in temperature excess depends on (i) the magnitude of the ELI trends, which is largest in initially energy-limited and transitional areas, and (ii) the initial ELI regime as (maximum) temperatures are more sensitive to evaporative cooling in initially water-limited regions.“

2) In support of this study, I think a huge advantage of this study is the use of ELI rather than soil moisture alone. This point is not clear in the study and I think it is one of the main points to make up front on why this complements existing literature so well. Most studies typically evaluate the question of how the land surface influences temperature extremes with soil moisture. However, because soil moisture is nonlinearily related to energy fluxes, it limits soil moisture’s use to evaluate temperature by itself. A more important variable that captures this nonlinearity and soil moisture variability simultaneously is how water-limited versus energy limited a location is. ELI is one nice way to capture this (my variable of choice is time spent in the water-limited regime). I suggest making this over point clearer throughout.

We have further clarified the benefits of using ELI over soil moisture alone in the introduction, the results and the conclusion.

“In particular we use (i) a recently introduced ecosystem water stress index (Ecosystem Limitation Index (ELI), (Denissen et al., 2020)), a correlative index that evaluates directly the importance of water versus energy stress for terrestrial evaporation, thereby moving beyond the nonlinear relationship between soil moisture and evaporative cooling alone. Further, as this index directly captures evaporative cooling, it links more mechanistically with heat waves than general aridity or land-atmosphere coupling indices. Thereby other factors affecting water-limitation can be functionally addressed (e.g. groundwater, hydraulic failure as lag effect, CO_2). Further, the ELI can be used to pinpoint regime transitions, as positive values are indicative of water-limited conditions, while negative values denote ecosystem energy limitation.”

“The sensitivity of temperature excess to ELI trends is expected to depend on the initial regime and can be explained through the nonlinear relationship between soil moisture and EF (Supplementary Figure 20 in Denissen et al., 2022; Seneviratne et al., 2010): In initially energy-limited grid cells (soil moisture exceeds critical soil moisture), ecosystems can sustain maximum EF, assuming sufficient available energy during the warm season. Hence, in such grid cells shifts towards water limitation, expressed by positive ELI trends or soil drying, do not amount to large changes in surface flux partitioning, nor in temperature excess, resulting in low sensitivity between ELI and temperature excess trends. In initially water-limited grid cells (soil moisture below critical soil moisture), further soil drying, or shifts towards water limitation, can reduce EF. This way, temperature excess trends are highly sensitive to ELI trends in water-limited grid cells. Transitional grid cells, which are characterized by a soil moisture regime that transitions periodically from below to above the critical moisture content, effectively switch between energy- and water-limited conditions frequently. As such, evaporative cooling and consequently temperature excess are periodically sensitive to increasing water limitation. In extremely dry and water-limited conditions, where soil moisture values approach the wilting point, hardly any moisture can be extracted from the soil, rendering vegetation activity and associated EF too low to provide ample evaporative cooling. As such, shifts towards ecosystem water limitation should hardly decrease evaporative cooling further in extremely water-limited grid cells."

"In conclusion, we show the ability of the land surface to modulate the intensity of future heat extremes. We focus on novel indices by focusing on ecosystem water limitation and the temperature excess between warm-season mean and maximum temperatures. In this context, the ELI is used to represent the nonlinear relationship between soil moisture and evaporative cooling, as it considers the effect of hydrometeorological anomalies on ecosystem response."

3) Language and bias of thinking throughout seems to be about how ELI is influencing excess temperatures and that the direction of causality is from ELI to excess temperature. For example, see lines 275-276. Following that, it is nicely stated that this correlative analysis does not mean causality. However, I do suggest also noting in the discussion or elsewhere how excess temperature can influence ELI. This might help complete the loop on that discussion since I think the feedback in the opposite direction of heatwaves on ELI is also just as interesting and valuable. In other words, the authors might be limiting themselves in influencing the reader to think about ELI influencing on temperature extremes, when the other way around can give insights about sustaining heatwaves.

A more elaborate discussion on the direction of causality between ELI and temperature excess is added in the results section.

"This is evidenced by significant correlations in many areas (Figure 1c, Supplementary Figure 6), suggesting that increasing ELI contributes to hotter temperature extremes. As correlations cannot distinguish the direction of causality, we stress that hotter temperature extremes can in turn further dry out terrestrial vegetation, thereby increasing water limitation. Additionally, heat extremes and related hydraulic failure could lead to plant mortality (McDowell & Allen, 2015), limiting evaporative cooling even more. As such, these pathways further strengthen positive correlations between ELI and temperature excess."

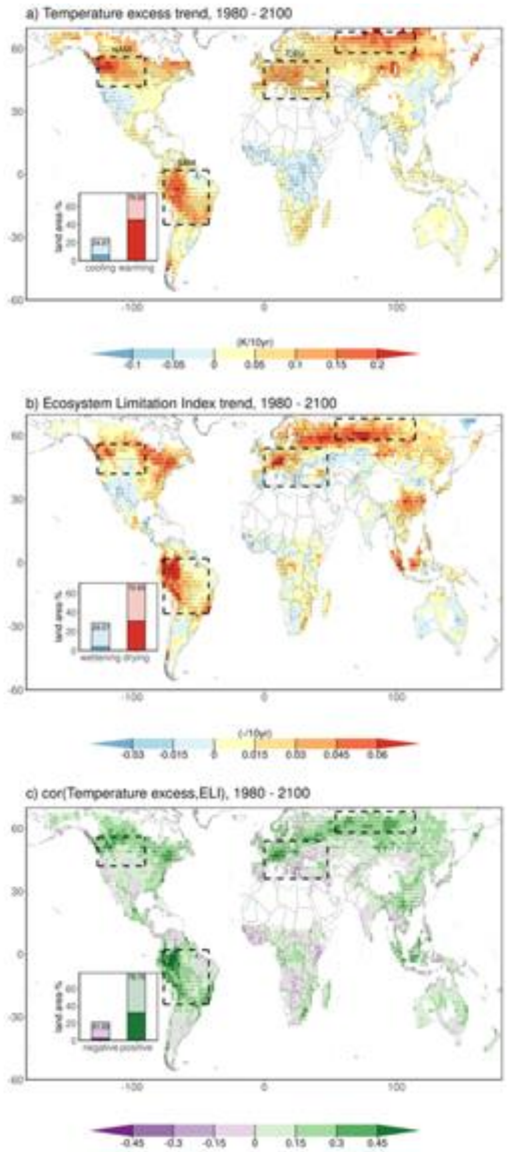
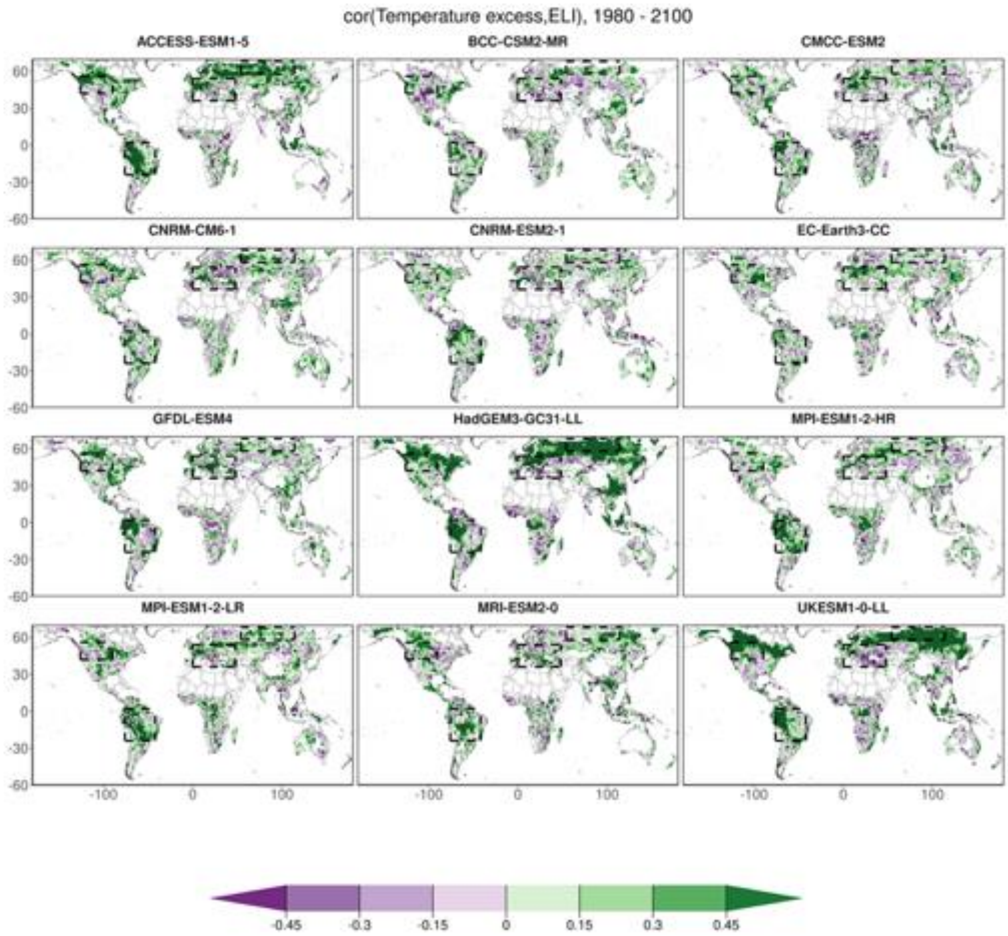


Figure 1. *Similarity of global patterns of change in temperature excess and ecosystem water limitation. Multi-model means of trends based on decadal time series per respective CMIP6 model of a) temperature excess) and b) Ecosystem Limitation Index (ELI). c) Multi-model means of Kendall's rank correlation coefficient between model-specific time series of ELI and temperature excess. The insets display the fraction of the warm land area with positive or negative trends or correlations, respectively (at least 8 out of 12 models agreeing on the sign of the trend or correlation are hued darker). Stippling indicates that at least 8 out of 12 CMIP6 models agree on the sign of the trend or correlation. All trends and correlations are calculated over the warm season and are only displayed if at least 8 CMIP6 models have full time series available, such that white areas denote regions with no or insufficient data. The dashed boxes indicate regions of interest, which are regions where temperature excess increases are particularly rapid and spatially coherent: North and South America (NAM and SAM), Central Europe (CEU) and Northern Asia (NAS).*



Supplementary Figure 6: *Kendall's rank correlation coefficient between ecosystem water limitation and temperature excess per individual CMIP6 model (dots indicate significance: p < 0.05).*

4) Figure 3 is really neat. I think it could be a better facilitated display of results in Fig. 3 and lines 231-247 if the nonlinear ET-soil moisture (and maybe also ET-SWin) relationships are discussed/displayed more prominently. I think the authors are making claims about how EF is insensitive to water in energy limited regions and might become even insensitive at lower soil moisture in water-limited places. These would be better supported if the Budyko framework and/or EF-soil moisture relationships are introduced before these other points are made about Figure 3.

We now explain the sensitivity of temperature excess to ELI trends at the hand of the nonlinear relationship between SM and EF as described by Seneviratne et al (2010). Further, we refer to Supplementary material in Denissen et al. (2020), where we find a strong link between the fraction of days with soil moisture below critical soil moisture and ELI:

"The sensitivity of temperature excess to ELI trends is expected to depend on the initial regime and can be explained through the nonlinear relationship between soil moisture and EF (Supplementary Figure 20 in Denissen et al., 2022; Seneviratne et al., 2010): In initially energy-limited grid cells (soil moisture exceeds critical soil moisture), ecosystems can sustain maximum EF, assuming sufficient available energy during the warm season. Hence, in such grid cells shifts towards water limitation, expressed by positive ELI trends or soil drying, do not amount to large changes in surface flux partitioning, nor in temperature excess, resulting in low sensitivity between ELI and temperature excess trends. In initially water-limited grid cells (soil moisture below critical soil moisture), further soil drying, or shifts towards water limitation, can reduce EF. This way, temperature excess trends are highly sensitive to ELI trends in water-limited grid cells. Transitional grid cells, which are characterized by a soil moisture regime that transitions periodically from below to above the critical moisture content, effectively switch between energy- and water-limited conditions frequently. As such, evaporative cooling and consequently temperature excess are periodically sensitive to increasing water limitation. In extremely dry and water-limited conditions, where soil moisture values approach the wilting point, hardly any moisture can be extracted from the soil, rendering vegetation activity and associated EF too low to provide ample evaporative cooling. As such, shifts towards ecosystem water limitation should hardly decrease evaporative cooling further in extremely water-limited grid cells."

5) This is a "devil's advocate" position, but something I worry about in studies using models to learn about land-atmosphere interactions is how much model biases in the relationships between soil moisture and energy fluxes (here EF) cause errors in results such as those presented here. I always look at CMIP or reanalysis based results and hope that ensemble means teach us emergent behavior of the land surface, rather than only give us back the potentially flawed relationship between soil moisture and EF that some models might have. This study is valuable in presenting the model results and also adds the dimension that projections can be made, which is not directly possible with observations. However, at least in the discussion, I suggest advocating for the main figures being reproduced in an observation-based study to test whether these model behaviors are reproduced in nature. For example, Figure 1c can be reproduced with satellite soil moisture and LST (or gridded air temperature) to give further support for the results here.

We agree with the reviewer. We assume that by taking a mean of many models with varying underlying assumptions on soil moisture and other stress functions. Even if this approach does not favor one model's flaws over the other, it is still based on a collection of model assumptions that need to be validated by observation-based studies. As time series of 120 years, as are used in this study, are not available from observation-based data sets, doing such an analysis would require a change in the methodology. Therefore, we think that this is out of scope for this analysis. However, we now advocate the need for observation-based analyses in the discussion, as the reviewer suggested.

"At the same time, the findings in this study are based on model-specific assumptions. Therefore, we advocate the need to reproduce the main findings in this study (Figure 1c, for example) with observation-based data to scrutinize the model-based findings in this study."

Further, we additionally advocate the use of observation-based data, as with time more and longer time series of observation-based variables will become available.

"This way, changes of both CO2 and climate jointly affect ELI which in turn influences heat wave magnitudes. Given this situation, future research should focus on the link between ELI and heat wave intensities using observation-based datasets, particularly as longer-term interpolations or reconstructions of key variables become available. This can help to corroborate model-based findings, and to constrain the variable relevance of ELI across models."

6) There are many figures in the SI that are discussed extensively in the results. For example, Figure S6 about ET in lines 164-174 and Figure S8 in lines 198-211. I suggest moving them to the main text if they are pivotal parts of the manuscript.

We agree with the reviewer here and have moved supplementary figures 6 and 8 to the main text (now Figure 2 and 4).

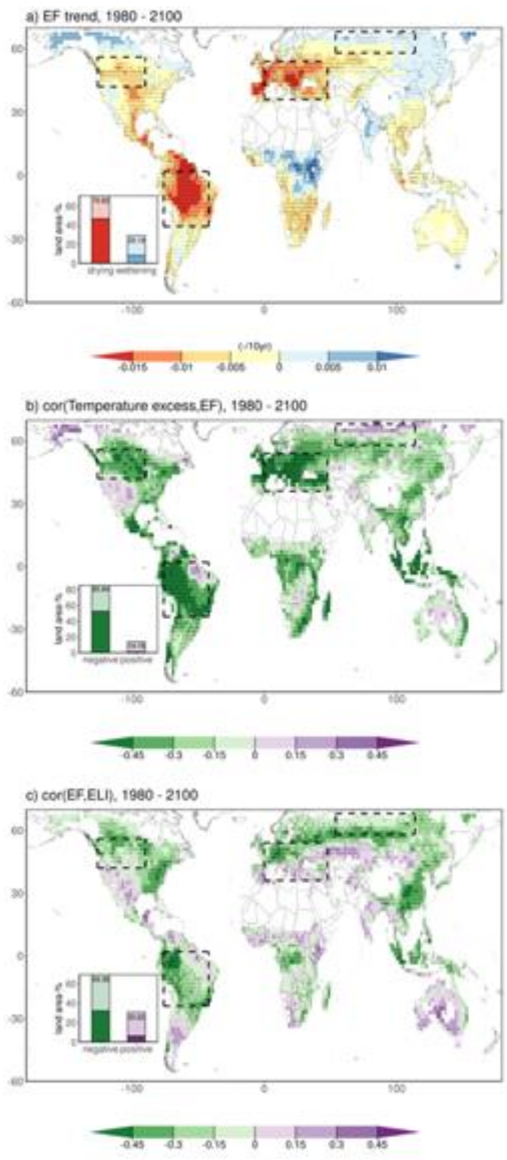


Figure 2. *Global multi-model mean distribution and trends of Evaporative Fraction (EF). Multi-model mean of trends based on decadal time series per respective CMIP6 model of a) EF and b) Ecosystem Limitation Index (ELI). c) Multi-model mean of Kendall's rank correlation coefficient between model-specific time series of ELI and temperature excess. The insets display the fraction of the warm land area that with positive or negative trends or correlations, respectively (at least 8 out of 12 models agreeing on the sign of the trend or correlation are hued darker). Stippling indicates that at least 8 out of 12 CMIP6 models agree on the sign of*

the trend or correlation. All trends and correlations are calculated over the three hottest months-of-year, defined as the 3 months–of-year which have the highest average temperature over 1980 - 2100. The dashed boxes indicate regions of interest.

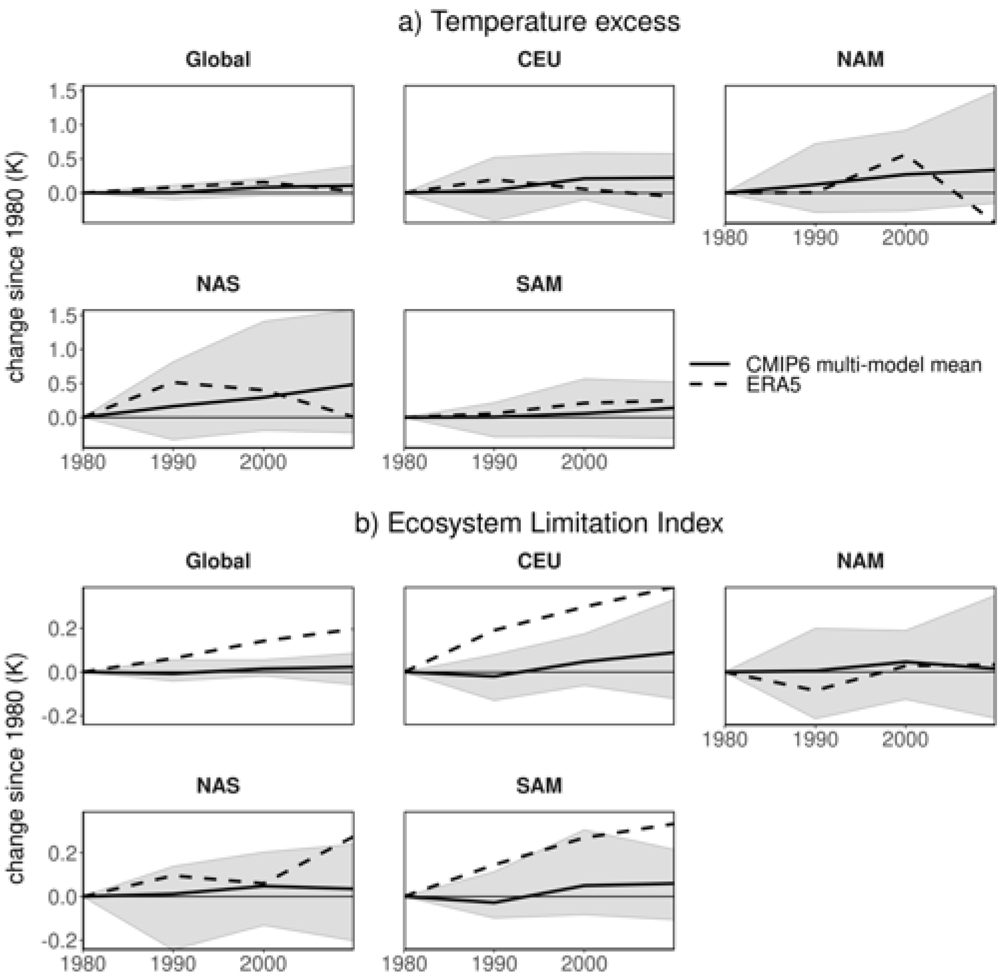


Figure 4. *Changes in global and regional temperature excess in concert with increasing ecosystem water limitation from CMIP6 models and ERA5-Land. Temporal evolution of a) temperature excess and of b) Ecosystem Limitation Index (ELI) globally and for the regions of interest. The black solid lines depict global and regional time series from the CMIP6 models, while the black dashed line represents ERA5-Land. The grey ribbon displays the envelope which encapsulates all the CMIP6 results. Global averages are calculated over land grid cells that have complete time series for all models and variables and are weighted according to the surface area per grid cell. The same mask is applied for CMIP6 models and ERA5-Land.*

Specific Comments

L12: note that the use of ecosystem (assuming both soil+vegetation) and vegetation are mentioned here which is making it unclear what the paper is about (is it only vegetation or soil+vegetation?). Potentially define what you mean by ecosystem here.

We clarify the use of ecosystem (both plant transpiration and soil evaporation) in the abstract.

“Heat extremes have severe implications for human health, ecosystems and the initiation of wildfires. Whereas they are mostly introduced by atmospheric circulation patterns, the intensity of heat extremes is modulated by terrestrial evaporation associated with soil moisture availability. Thereby, ecosystems provide evaporative cooling through plant transpiration and soil evaporation, which is reduced under drought stress.”

L70: The “|” symbol indicates conditioning in mathematics/probability. It is unclear how it is being used in the correlation function “cor(Ta’|SWin’,ET’).” It sounds like the correlation is either between Ta and ET or Ta and SWin based on line 75. Therefore, I think the “|” symbol is being used to somehow indicate this potential alternation in the metric. However, one can also interpret that notation as the correlation of Ta’ with ET’ while conditioning (or binning) Ta’ on SWin’. Can the authors be clearer about this notation? I know L85 says to refer to another study for details of ELI, but details like this should be shared here for completeness.

We explain the notation in the following lines:

“In this context, the | indicates the use of either Ta or SWin anomalies in the second term on the right hand side of Eq. 1, as ET in some regions is limited more strongly by lack of incoming shortwave radiation (Nemani et al., 2003) and in other regions more strongly by cold temperatures.”

L95, Table 1: It might be worth noting what the difference in r1/r2 and f1/f2 mean since not all are the same in that column.

In the current selection there are only differences in f1/f2/f3, which are now explained in the caption of Table 1.

“*: in the CMIP6 members, or variants, differences exist in the forcing index (f). This index number indicates the forcing used for the respective realization and can be used to distinguish between CMIP6-recommended or other forcing data sets. Which forcing dataset f represents is defined per model.”

L114-115: The LAI condition at 0.5 m2/m2 might be overly restrictive and remove many drylands from the analysis that are important facets of the global climate.

See answer to 1).

L115: Central Africa? Do you mean East Africa?

We have adapted to “Northern Africa”.

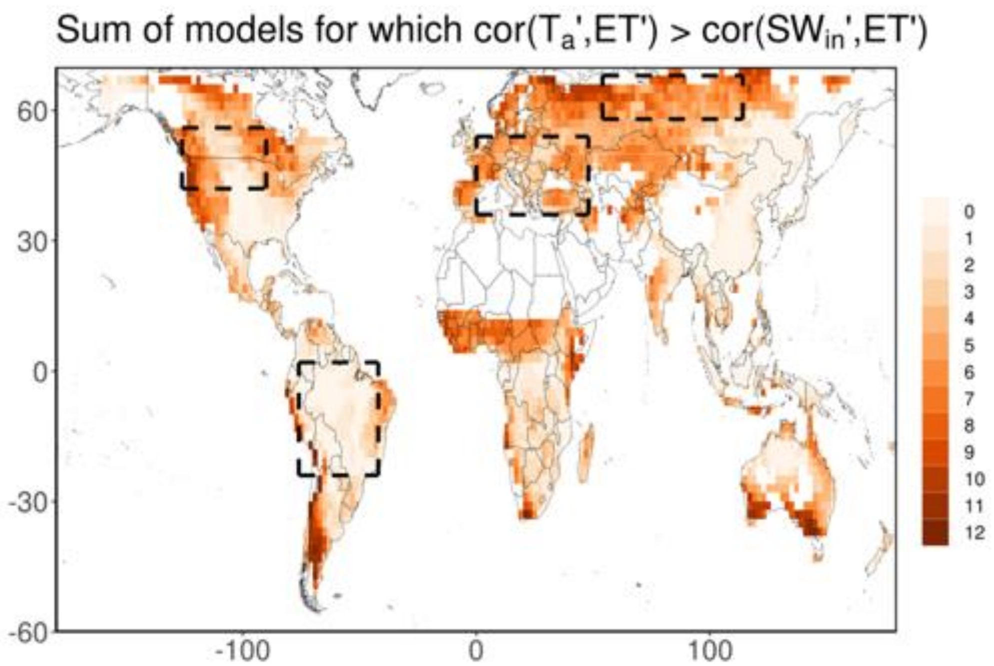
L118: It should be the sum of radiative components minus the ground heat flux (G) (or Rn-G).

We decided to neglect ground heat flux in our analysis, as we do not expect that it can significantly influence trends in ecosystem water limitation or excess heat. It is more relevant on a diurnal scale of course.

L150-152: This statement is tough to follow. This is only referring to the second term on the right side of Equation 1 or the energy limited component of ELI? I was thinking that water-limitation should be a big component in the tropics (but it looks like water-limitation is not considered in Fig. S1)

We have adapted the writing to more clearly explain that this indeed concerns only the second term on the right hand side of Equation 1:

"cor(SM',ET') is a proxy for water limitation, whereas cor(Ta' | SWin',ET') is a proxy for energy limitation. In this context, the | indicates the use of either Ta or SWin anomalies in the second term on the right hand side of Eq. 1, as ET in some regions is limited more strongly by lack of incoming shortwave radiation (Nemani et al., 2003) and in other regions more strongly by cold temperatures. Therefore, we test for each grid cell which energy proxy yields the highest correlation with ET (cor(Ta',ET') vs. cor(SWin',ET')), and is hence most relevant in this location, to then use it in the computation of ELI in the respective grid cell (Supplementary Figure 1)."



Supplementary Figure 1: *Spatial distribution of the sum of models that are temperature-controlled. Colors show the sum of models for which cor(Ta',ET') > cor(SWin',ET') over 1980 – 2100.*

L157-158: It could be the other way around where temperature extremes contribute to increasing ELI.

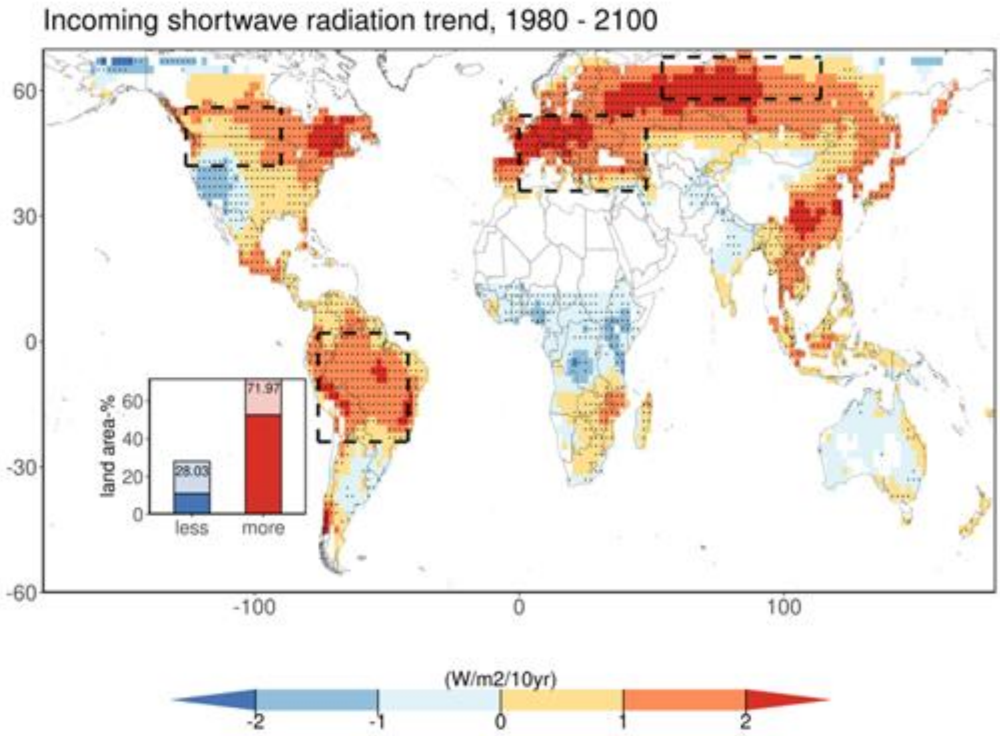
See answer to 3).

L158-L160: With removal of many drylands and some opposing results in these locations (see my comment 1), it would be worth discussing further what physical processes cause these regions to differ.

We have added Supplementary Figure 4, which shows that in regions with insignificant or negative correlations between ELI and temperature excess, trends in incoming shortwave radiation are generally also negative. We discuss this in lines XXX-XXX

Lines XXX-XXX

“Further deviations from a positive relationship between temperature excess and ELI might result from alternative processes such as (changes in) advection of warm air masses through large-scale circulation patterns and changes in incoming shortwave radiation (Supplementary Figure 4).”



Supplementary Figure 4: *Multi-model mean trend in incoming shortwave radiation based on decadal time series per respective CMIP6 model. The insets display the fraction of the warm land area with positive or negative, respectively (at least 8 out of 12 models agreeing on the sign of the trend are hued darker). Stippling indicates that at least 8 out of 12 CMIP6 models agree on the sign of the. All trends are calculated over the warm season and are only displayed if at least 8 CMIP6 models have full time series available, such that white areas denote regions with no or insufficient data. The dashed boxes indicate regions of interest, which are regions where temperature excess increases are particularly rapid and spatially coherent: North and South America (NAM and SAM), Central Europe (CEU) and Northern Asia (NAS) (see Figure 1).*