Supplementary Material: Irrigation and hydrometeorological extremes

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References

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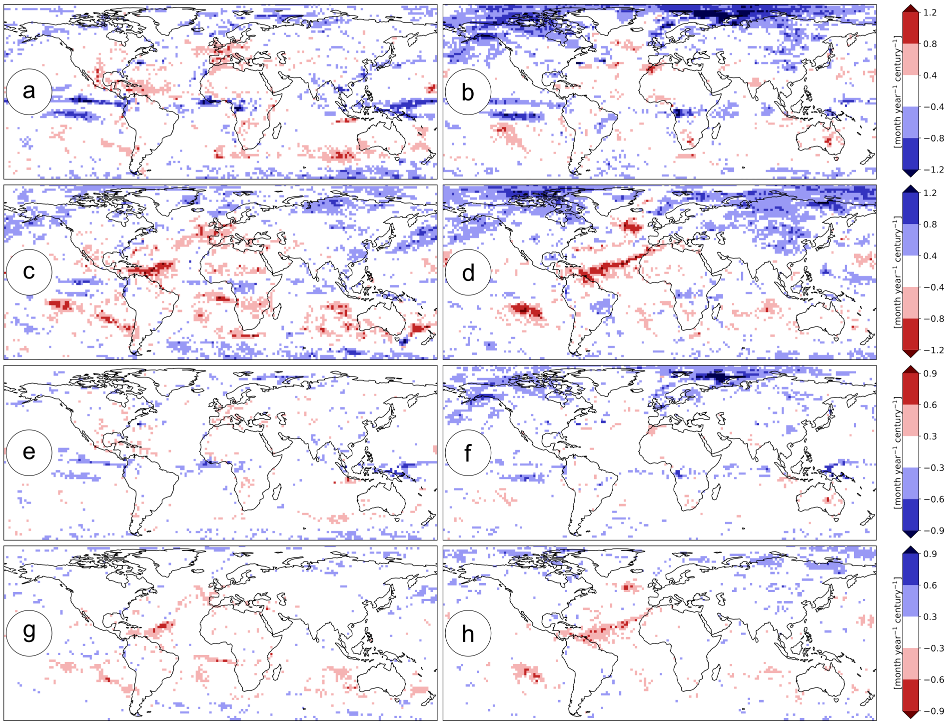

Figure S1: **Trends in the occurrence frequency of severe and extreme precipitation due to the increase in GHG concentration.** Sub-figures show the same as in Fig. 7 but for trends that result from increasing GHG concentrations.

The increase in GHG concentrations of the RCP4.5 scenario significantly alters the frequency of severe and extreme precipitation rates. However, the largest changes occur over the ocean and, as a result, have only a minor feedback on the climate system. Here, three latitudinal zones can be distinguished which roughly follow the shifts in the annual mean precipitation. Close to equator, increases in precipitation during both half-years lead to an increase in the number of severely wet months that, on average, occur during a year (Fig. S1c,d). At the same time, these regions show decreases in the occurrence frequency of severely dry months of up to -1 month year^{-1} century^{-1} (Fig. S1a,b). In the largest parts of the globe, between about 10°N - 45°N and 10°S - 45°S, there are only few areas that are significantly affected, with the most pronounced signal being a decline in precipitation that leads to positive trends in the occurrence of severely dry month and even larger negative trends in the occurrence of severely wet months. A notable exception in this region is East Asia where, especially during the boreal winter, there is a substantial increase in the average number of severely wet months per year and a decline in the number of severely dry months. The increase in GHG concentrations has its largest effect in high northern latitudes, where also the increase in the annual mean temperature is strongest. Especially during winter, the number of severely dry months that occur during a year, decreases by as much as -1.5 month year^{-1} century^{-1} , with the increase in severely wet months being only slightly smaller. Thus while there are regional increases in the occurrence frequencies of both severely wet and dry month, these are often accompanied by a decrease at the opposite end of the precipitation spectrum. Consequently, there are regional shifts in the occurrence frequency of severe conditions from severely dry to severely wet (close to the equator and in high northern latitudes) and shifts from severely wet towards severely dry conditions (in the regions 10°N - 45°N and 10°S - 45°S), but there is no clear indication that the warming trend amplifies the overall occurrence frequency of periods with severe precipitation rates.

For extreme precipitation, there is even a tendency that the decrease in the occurrence frequency at one end of the precipitation spectrum is larger than the increase at the other end. Here, the most distinct signal during summer is a reduced occurrence of extremely dry months close to the equator and a decrease in the average number of extremely wet months per year between 10°N - 45°N and 10°S - 45°S (Fig. S1e,g). For winter, the most distinct trends correspond to a decrease in the number of extremely dry months in high northern latitudes and a decrease of extremely wet months over the North Atlantic (Fig. S1f,h). Here it should be clarified that the overall occurrence frequency of severe and extreme conditions, i.e. wet and dry combined, can not be used as an indicator for the risks they entail. For example, by the end of the 21st century, the trends in Europe and northern Africa (about 0.5 month year^{-1} century^{-1}) will, on average, lead to one additional severely dry month every second summer. This increase in meteorological droughts could have extremely detrimental consequences for the agricultural productivity in the region, which may be completely uncompensated by the reduced occurrence frequency of severely wet months.

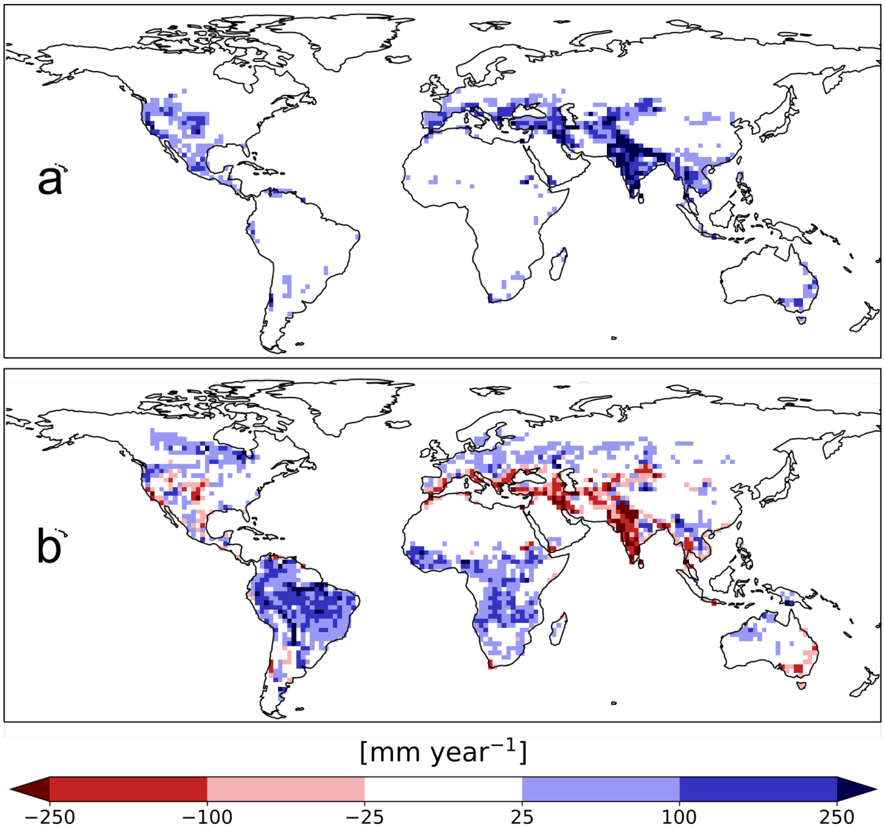

Figure S2: **Irrigation in the reference setup and the setup that maximizes irrigation within sustainable limits.**

a) Annual irrigation with the reference setup (present-day). **b)** Difference between maximum sustainable and reference irrigation in the year 2050.

With close to 3000 km^3 a^{-1}, the annual irrigation volume of the reference simulations is at the higher end of estimates from previous studies, which range roughly between 1000 - 3000 km^3 a^{-1}, for present-day (Wada et al., 2013; Yoshikawa et al., 2013). The (reference) irrigation scheme is very simple in that we prescribe the (present-day) observed irrigated areas and assume that enough water is available for these areas to be irrigated. In JSBACH, the irrigation demand depends strongly on the assumptions made with respect to the irrigation characteristics but also on the overall model structure the irrigation scheme is embed into. In a previous study we found that the simulated, present-day irrigation demand varied between 400 km^3 a^{-1} and 6800 km^3 a^{-1} depending on the assumptions made with respect to the irrigation target (given by the desired saturation of the soil), the representation of irrigation as a sub-grid-scale feature and the land-surface-atmosphere coupling (de Vrese and Hagemann, 2017). For the present study, the simulated irrigation volume could have been reduced substantially – to better fit observations – by reducing the irrigation target. However, gross irrigation is not necessarily a good reference for tuning the model. In the model, a large fraction of the irrigation has little consequences for the simulated climate because the water is not transpired (or evaporates), but simply drains from the soil and this fraction increases with higher irrigation targets. The model does not represent sub-grid-scale variability of soil properties – while in reality cropped areas are often chosen for their soil properties – or constructive features such as embankments. Thus, the model can not simulate highly saturated soils that are given for common irrigation techniques, such as rice paddies, without overestimating runoff and drainage. This means that a good estimate of the evapotranspiration from irrigated areas, hence the respective impacts on climate, will result in an overestimation of the gross irrigation quantities. For the idealized setting of this study, we assumed the irrigation target to be the (soil's) level of saturation at which plants have the highest productivity and highest transpiration rates, even though this results in comparatively high simulated irrigation fluxes.

When irrigation is maximized within sustainable limits the overall irrigation volume increases to about 5500 km^3 a^{-1}, and there is distinct shift from irrigation in (semi) arid regions – especially in the subtropics of the northern hemisphere – towards more humid regions such as the temperature zone in the northern hemisphere but also tropical South America and Africa. This also means that a much smaller fraction of the irrigation water evaporates or is transpired – because the atmospheric moisture demand is much lower in the more humid regions – and a larger fraction drains from the soil. As the drainage enters the channel flow, it can be used for irrigation in downstream grid-boxes allowing a higher recycling rate and, consequently, much higher gross irrigation rates.

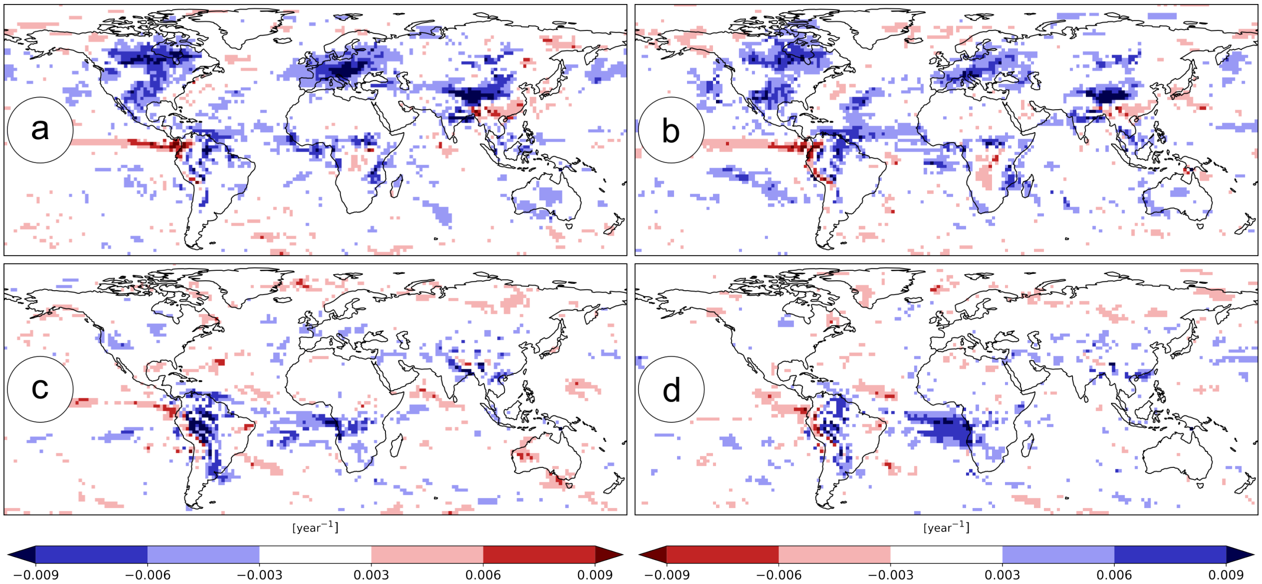

Figure S3: **The SPI on a 6-months time scale:**
a) Difference in the trend in the SPI (2000-2100) between IR45 and RF45. The SPI is calculated for the precipitation sum over the summer. Only negative SPIs, reflecting dry conditions, are taken into account. **b)** Same as *a*, but for positive SPIs reflecting wet conditions. **c)** Same as *a*, but for winter. **d)** Same as *b*, but for winter.

Estimating the SPI for short time scales of less than 3 months, can result in very large positive or negative values in arid regions (Lloyd-Hughes and Saunders, 2002). To confirm that our findings do not originate from this potential bias of the SPI, we calculated the SPI for periods of 6 months instead of a monthly time scale and compare the trends in the SPI directly. For this 6-months time scale, the regions in which the trends differ robustly between the irrigation and the no-irrigation time series compare very well with the regions where also the analysis of the number of months with severe and extreme precipitation showed significant effects (compare e.g. Fig. S3 to Fig. 7). In fact the irrigation-induced signal appears to be even clearer when using this measure. However, the differences in trends in the SPI, do not provide information on the development of extremes or severe events. For example, in regions where irrigation has a strong effect, the SPI differs by about 1 [/ century$_{-1}$]. But it is unclear whether this difference indicates a shift from moderate to extreme (or vice versa) or from mild to severe conditions or whether the index merely changes between mildly dry and mildly wet conditions.

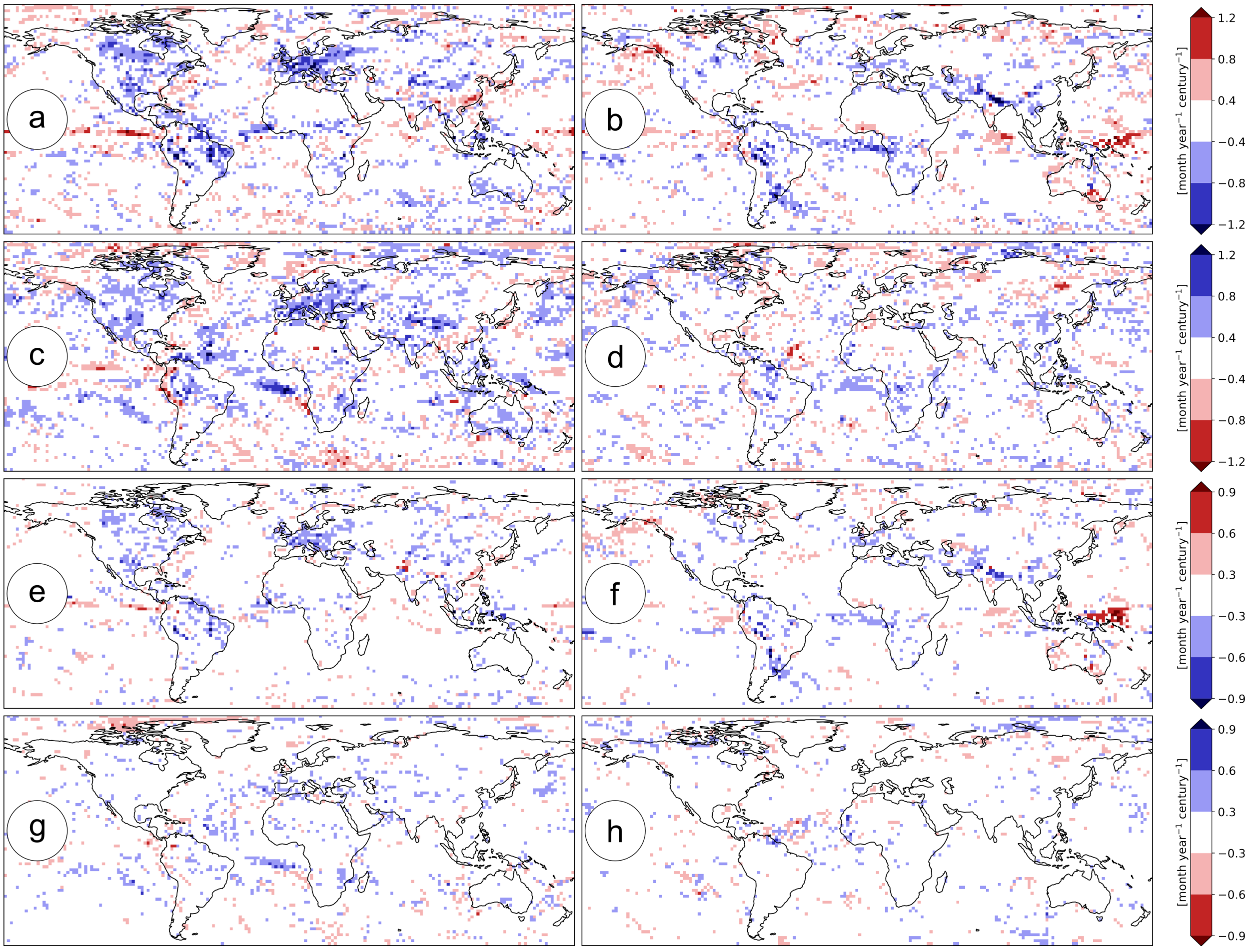

Figure S4: **Impact of irrigation when shortening the reference period to 30 years:** **a)** Difference in trends (number of severely dry months that occur during summer) between IR45* and RF45*. **b)** Same as *a*, but for winter. **c)** Difference in trends (number of severely wet months that occur during summer) between IR45* and RF45*. **d)** Same as *c*, but for winter. **e)** Difference in trends (number of extremely dry months that occur during summer) between IR45* and RF45*. **f)** Same as *e*, but for winter. **g)** Difference in trends (number of extremely wet months that occur during summer) between IR45* and RF45*. **h)** Same as *g*, but for winter. Non-significant differences ($p > 0.05$) are masked in all subplots. The scenarios IR45* and RF45* are constructed in the same way as IR45 and RF45 with the difference that, only the first 30 years of each precipitation time series contain the records of the reference simulations instead of the first 50 years.

For the irrigation and the no-irrigation scenarios, the trends in the occurrence frequency of severe and extreme condition also depend on the way the scenarios are constructed, i.e. for how long the precipitation rates of the reference simulation are assumed at the beginning of the precipitation time series. Here, the choice was to a certain degree arbitrary and there is no indication that the scenarios reflect real-world developments. To identify to which extent this choice of reference period influences our results, we repeated the analysis for two additional scenarios, IR45* and RF45*, which are constructed in the same way as IR45 and RF45 but with only the first 30 years of each precipitation time series containing the records of the reference simulations instead of the first 50 years. A comparison between IR45*-RF45* and IR45-RF45 (compare Fig. S4 to Fig. 7) shows that the general impact of irrigation on the occurrence of severe and extreme conditions remains largely the same, however, in many regions, the magnitude of the impacts is slightly smaller when shortening the reference period to 30 years. This is more pronounced for the impact on the occurrence frequency of severely and extremely dry conditions than on the occurrence frequency of severely and extremely wet conditions and, as a consequence, the benefits of irrigation, i.e. the reduction of severely and extremely dry months, do not prevail as clearly over the respective risks, i.e. an increase in the occurrence frequency of severely wet months.