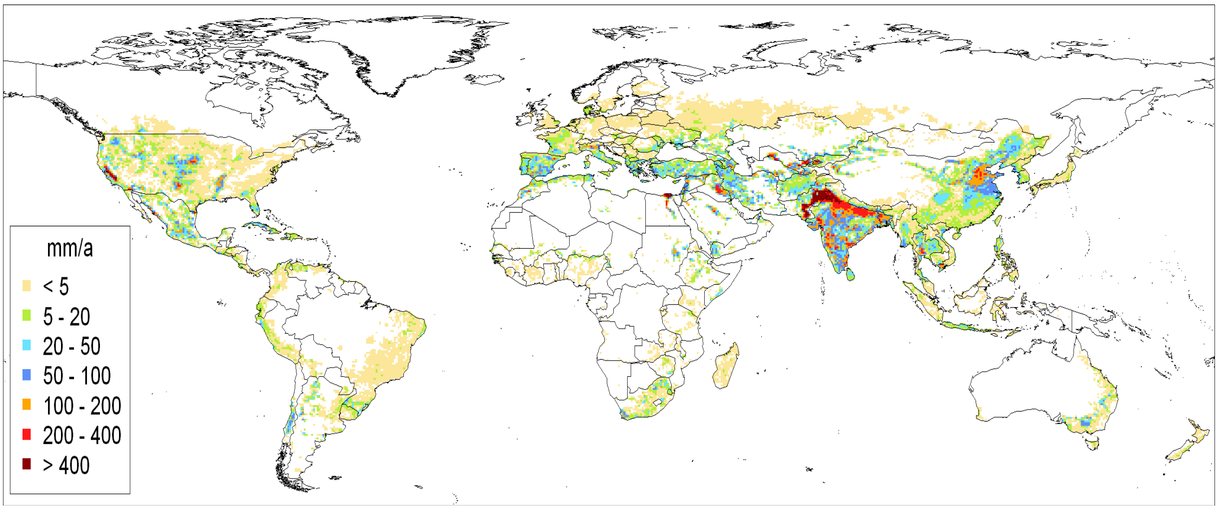
Technical Report No. 47

CLIMATE CHANGE AND IRRIGATION: GLOBAL IMPACTS AND REGIONAL FEEDBACKS



Present irrigation demand simulated by the LPJmL model

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Title:	Climate Change and Irrigation: Global Impacts and Regional Feedbacks
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This report summarises work done in WATCH's Work Block 3 on the effects of human activities on climate and the water balance and, vice versa, on climate impacts upon human water withdrawal. It includes three (preliminary) studies concerned with 1) impacts of potential future irrigation on regional climate (in southern Asia); 2) impacts of 21st century climate change on irrigation requirements globally; and 3) effects of dams on global river discharge.

1 Impact of irrigation on the climate change signal over South Asia

In the recent past, there have been many studies highlighting the importance of irrigation in influencing the local climate of different regions of the world. Within the WATCH project, several studies were conducted focusing on the role of irrigation in affecting the climate of South Asia. The study in WB3 carried out by Saeed et al. (2009) using the regional climate model REMO (Jacob et al. 2007) showed the removal of a 5°C temperature bias over the north-western India and Pakistan region if irrigation is represented properly. In another WATCH WB3 study, Lucas-Picher et al. (2011) found a similar bias in other regional climate models and concluded that the lacking representation of irrigation in all those models to be the main cause of the bias. More recently, a further WATCH (WB5) study by Tuinenberg et al. (2011) yielded a positive precipitation trend in the climate stations located in the irrigated regions of South Asia. All these studies pointed towards irrigation causing lower temperatures due to utilisation of energy in evaporating the available water instead of warming the surface. Moreover, the evaporation will increase the availability of moisture for convection and, therefore, precipitation.

South Asia is a region known to be severely threatened by climate change. Therefore, in continuation of the above-mentioned studies, we addressed the possible impact of irrigation on the future climate of South Asia. For this purpose, regional climate model simulations were carried out with the REMO model using GCM forcing data from an ECHAM5/MPIOM (Roeckner et al. 2003; Jungclaus et al. 2006) simulation ("ECHAM5" henceforth) following the A1B scenario. Three time periods were chosen for these simulations, where each period was preceded by a 2 years simulation to account for model spin-up that is not considered in the analyses:

i. Control (1985-1999)
ii. Scenario I (2035-2049)
iii. Scenario II (2085-2099)

The results of the control simulations (Fig. 1) show that REMO has well downscaled the ECHAM5 data. Especially the orographically induced precipitation highs over the Western Ghats and foothills of Himalaya are represented better in the REMO model due to its higher resolution as compared to ECHAM5. Moreover, the rain-shadowed area on the east of Western Ghats and high over central India are also well simulated by the model. However, REMO shows the similar acute temperature bias of more than 5°C as was present in ECHAM5 simulation over north-western India and Pakistan.

In order to represent the irrigation in REMO, we have adopted the same methodology as presented by Saeed et al. (2009) with increasing the soil wetness at each time step to a critical value so that potential evapotranspiration may occur. As in their study, we have again observed the removal of the warm and dry biases over the regions of northwest India and Pakistan, thereby showing the better simulation of these variables with the inclusion of an irrigation scheme in the REMO model.

For the climate change simulations, the results of Scenario II (2085-2099) minus control (1985-1999) are presented in Fig. 2. Here, it is shown for the projected changes in 2 m temperature that ECHAM5 and REMO without irrigation project an increase of more than 4℃ in general and more than 6℃ over the central Indian region. In contrast, the REMO simulation with irrigation projects much less warming as compared to the other two simulations, with a temperature increase ranging from 2℃ to 4℃. For precipitation, both REMO versions with and without irrigation show similar climate change signals, with a decrease of precipitation over the northern Indian region and an increase in precipitation over the southern peninsular. Here, the signal projected by both REMO versions is different from that of ECHAM5, which shows a decrease of precipitation over the whole of South Asia except for Bangladesh and northeast India, where the model projects an increase.

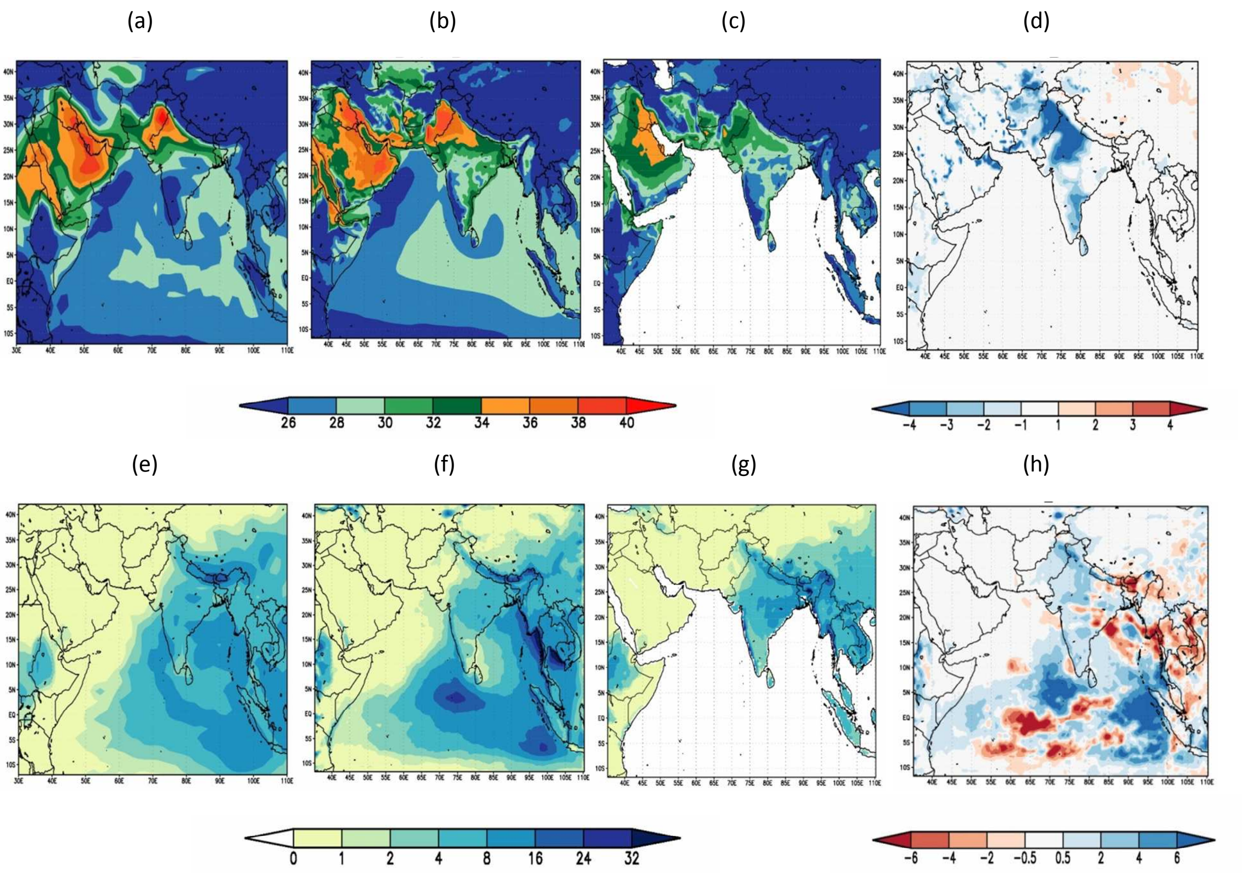


Fig. 1: 2m temperature in ℃ (upper panel) and precipitation mm/day (lower panel) results for the control simulation and observations. The results of ECHAM5 (a and e), REMO without irrigation (b and f), observations (c for CRU data, Mitchell & Jones 2005, and g for data of Wilmott & Matsuura 2009) and REMO without irrigation minus REMO with irrigation (d and h) are presented.

The present study highlights the role of irrigation in attenuating the climate change signal over the South Asian region. Thus, it can be concluded that the irrigation performed over the 20th century may have already masked recent climate change signals over this region. The difference in the signals of 2m temperature between both versions of REMO (with and without irrigation) illustrates the importance of the representation of irrigation for carrying out any study over the South Asian region using climate models.

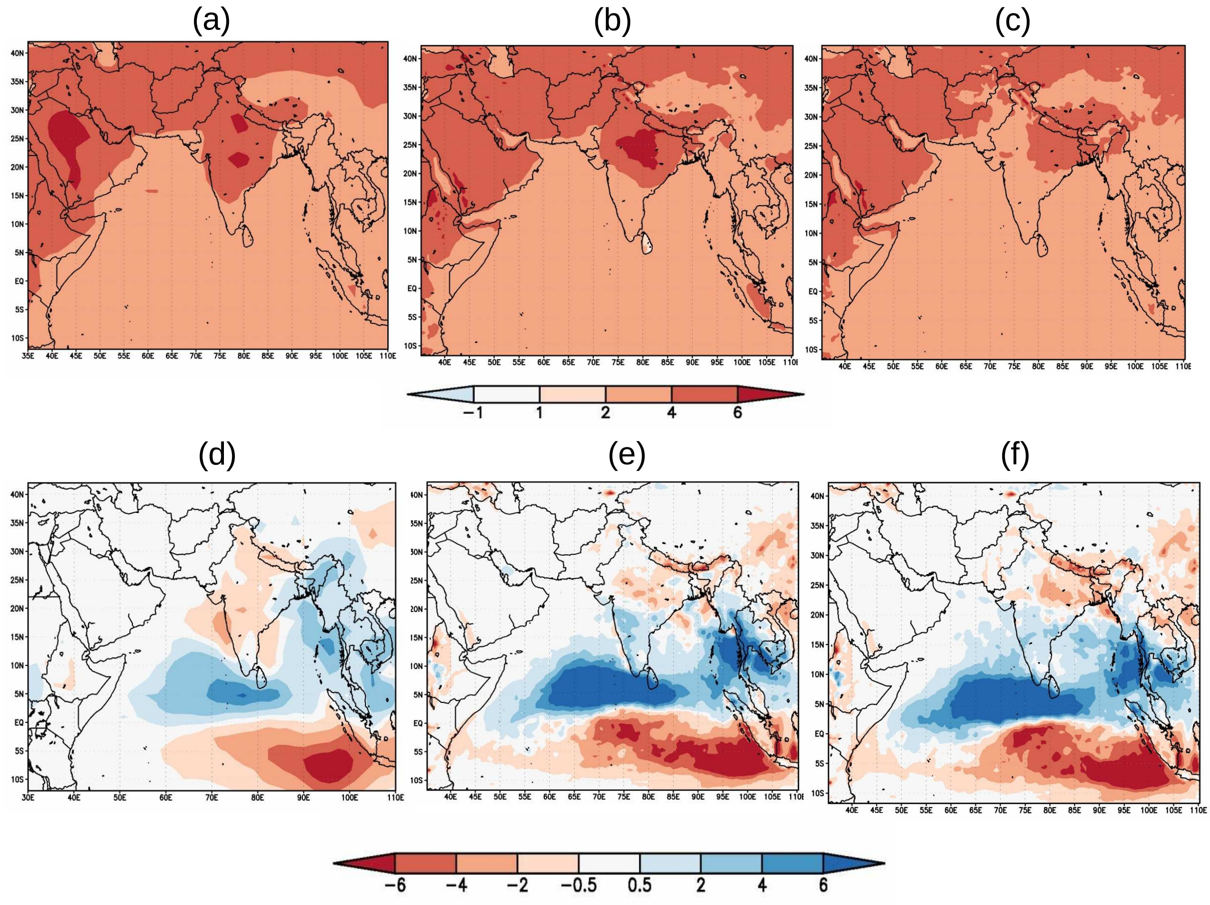


Fig. 2: Scenario II (2085-2099) minus Control (1985-1999) simulation for 2m temperature in ℃ (above panel) and precipitation in mm/day (lower panel). The results of ECHAM5 (a and d), REMO without irrigation (b and e) and REMO with irrigation (c and f) are presented.

2 Impacts of climate change on global net irrigation requirements

A further set of – global – simulations to quantify irrigation effects in the future has been performed at PIK using the LPJmL global vegetation and water balance model. The objective of these simulations was not to estimate impacts of irrigation, dam construction, land use changes or other anthropogenic activities upon the water cycle, but – other than in above study – to assess the impacts of climate change on irrigation requirements (from which conclusions about required changes in irrigation needs and related feedbacks to the water cycle can be qualitatively deduced). The core methods and preliminary key results of this impact analysis are summarised in the following sections.

Calculation methods are based on Rost et al. (2008) who describe in detail the irrigation module embedded in the LPJmL model used in this study. Overall features of LPJmL and particularly its crop modelling procedures are described in detail in Bondeau et al. (2007), while the land use dataset used here – present and historical constructions of irrigated and rainfed crop areas and pastures, with rainfed and irrigated crop areas held constant at the year 2000 values in the future – are characterised in Fader et al. (2010). Climate inputs, i.e. monthly CRU TS 3.0 temperature, precipitation and cloudiness up to year 2000 (Mitchell & Jones 2005; http://badc.nerc.ac.uk/data/cru/) here disaggregated to daily values, and 19 GCMs for the subsequent transient simulation period up to year 2100 (CMIP3 participants; https://esg.llnl.gov:8443/home/publicHomePage.do), were the same as in Gerten et al. (in press). All simulations were performed at 0.5° x 0.5° spatial resolution, and the underlying processes (water and carbon stocks and balances, vegetation dynamics) were simulated at daily time steps, though aggregated in this report to annual totals averaged over 30-yr time slices ("present", 1971–2000; "2080s", 2070–2099). A full account of the present results along with more detailed explanations of processes underlying the simulated changes in irrigation requirements are provided by Konzmann (2011) and will be published in a forthcoming paper (Konzmann et al., in preparation).

In a first step, the LPJmL model was applied to quantify the present net irrigation requirements (NIR), defined as the amount of "blue" water from rivers, lakes, reservoirs and aquifers needed to ease water limitation of crops on areas currently equipped for irrigation. NIR is computed as a function of potential evapotranspiration, atmospheric CO_2 concentration, soil moisture, crop water limitation, duration of the growing period of the 11 major crop functional types considered (which can shift in response to climatic changes), and irrigation efficiency as estimated for each country (Bondeau et al. 2007; Rohwer et al. 2007; Rost et al. 2008; Konzmann 2011). NIR is different from gross irrigation requirement, which is the amount of water that actually needs to be withdrawn – this amount is always higher, because part of the withdrawn water is lost on its way to the field, as determined by the irrigation efficiency.

As a result, present (1971–2000 average) NIR was found to be 1029 $km^3\ yr^{-1}$ globally (gross irrigation requirements, 2709 $km^3\ yr^{-1}$), which agrees well with earlier studies. As shown in Fig. 3 (upper map), highest NIR values per 0.5° grid cell occur in regions where irrigation areas cover large fractions of total grid cell area, particularly in northern India, parts of Pakistan, parts of the western U.S., and along several river stretches such as the lower Nile. Highest values per irrigated area (Fig. 3, lower map) are typical for most subtropical and tropical irrigation areas on all continents, mostly because atmospheric irrigation demand (potential evapotranspiration) is high in these regions compared to temperate zones.

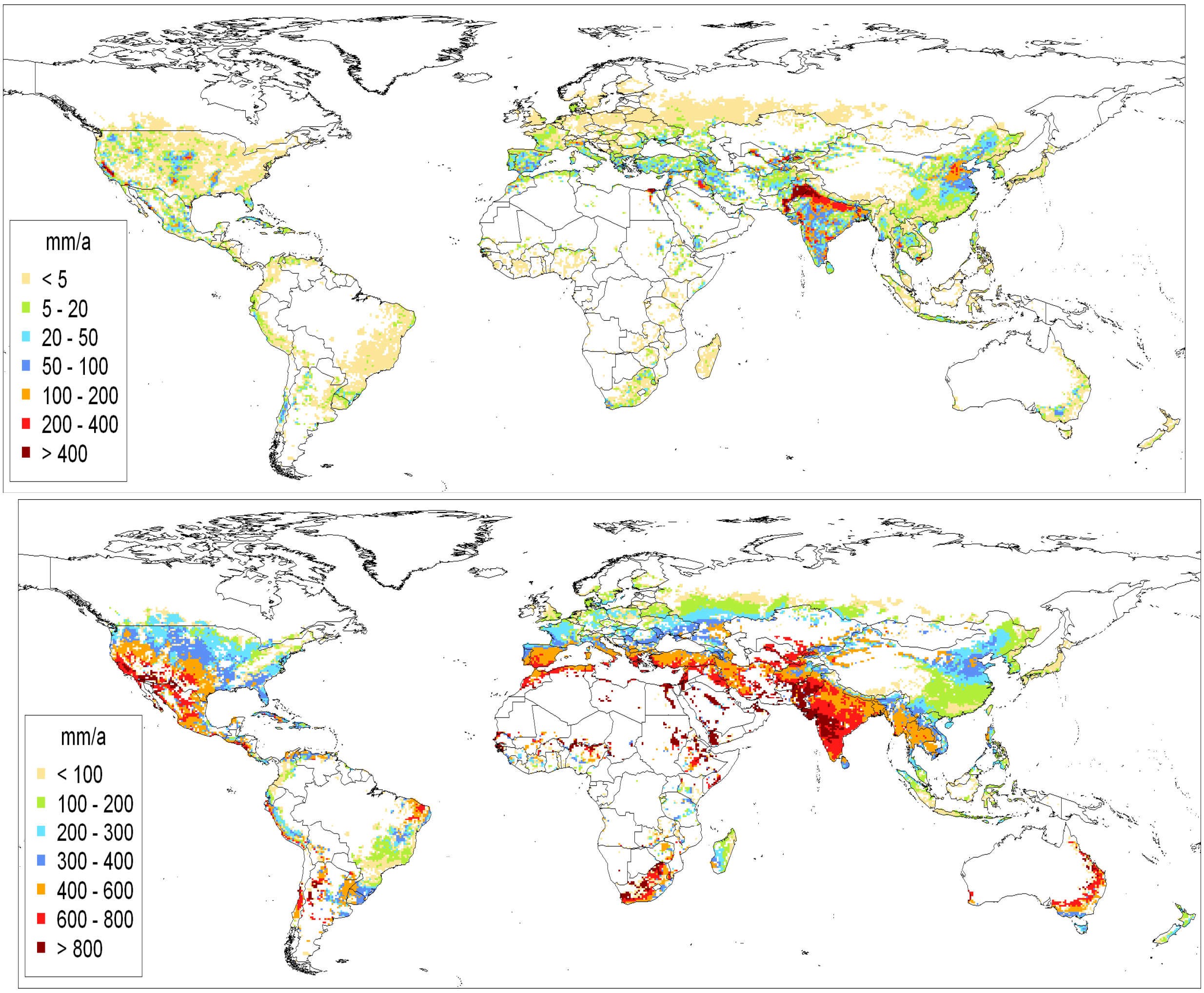


Fig. 3: LPJmL-simulated annual net irrigation requirements (NIR, in mm yr^{-1}), averaged over the period 1971–2000. Top: values per grid cell (incl. non-irrigated areas) highlighting the areal extent of irrigation areas; bottom: values per irrigated area in a grid cell, highlighting the climatic effect.

As one can depict from Fig. 4 (below), NIR will change considerably in many regions in response to climate change. Increases in NIR – i.e. higher needs of blue water – are simulated for the currently irrigated areas in southern Europe, parts of Asia and the U.S., whereas many parts of South Asia, including large irrigation areas in India (compare Fig. 3), are simulated to benefit from a decrease in NIR (note though that patterns of change differ much across GCMs, as exemplarily shown in Fig. 5). This is also reflected in the modelled change in global NIR, which progressively decreases over the 21^{st} century (Fig. 6). The decrease amounts to 9–19% by the 2080s depending on the climate scenario. While part of this – perhaps unexpected – decrease in NIR can be explained by higher annual and seasonal precipitation simulated by most GCMs (including over large parts of India; Konzmann 2011), the rise in atmospheric CO_2 concentration – which leads to earlier stomata closure resulting in higher water use efficiency and lower transpiration at the leaf level (e.g. Leipprand & Gerten 2006) – tends to decrease NIR in many regions. Actually, according to our analysis global NIR would increase rather than decrease if the CO_2 effects were omitted from the analysis. Any study of future changes in irrigation demand (and water resources and water scarcity in general) should however consider these effects, as they have been reported in numerous field and laboratory studies and as they were found to contribute already to global changes in evapotranspiration and river discharge (see Gerten et al. 2008, and references there).

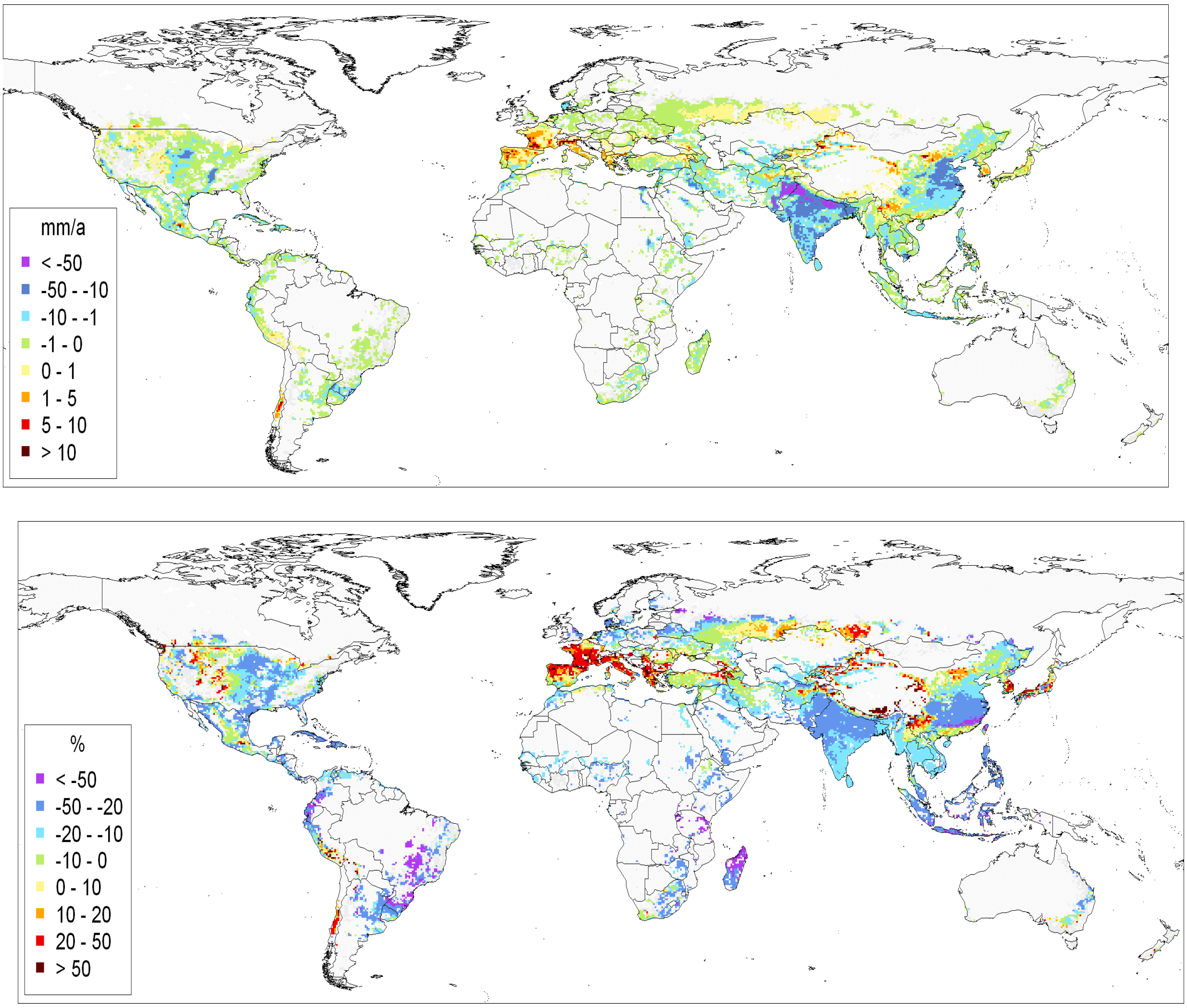
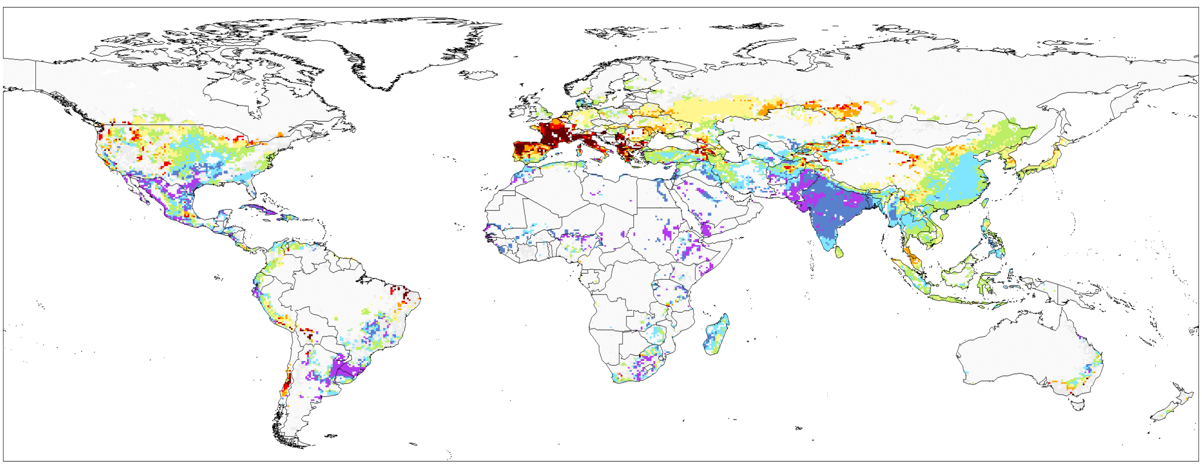


Fig. 4: LPJmL-simulated change in net irrigation requirements (top, in mm yr^{-1}; bottom, in %) by the 2080s relative to the present, portrayed as the median across the 19 GCMs used to force the LPJmL model. Values are given per grid cell as in Fig. 3, top.



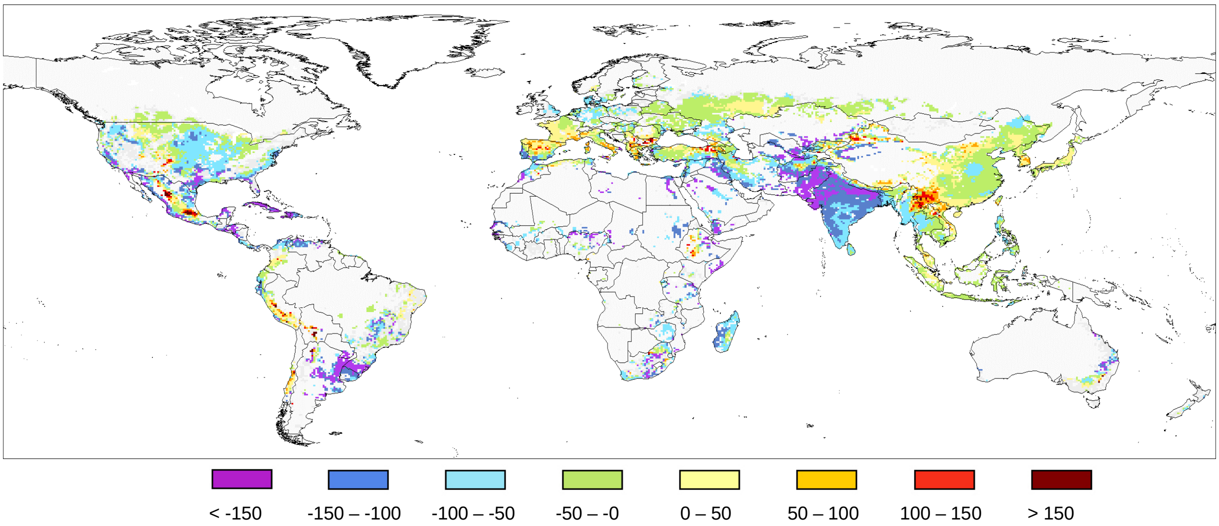


Fig. 5: Change in net irrigation requirements (mm yr^{-1}; bottom, in %) by the 2080s compared to the present, under climate projections from two GCMs: UKMO's HadCM3 model (upper map) and CSIRO's MK3.0 model (lower map).

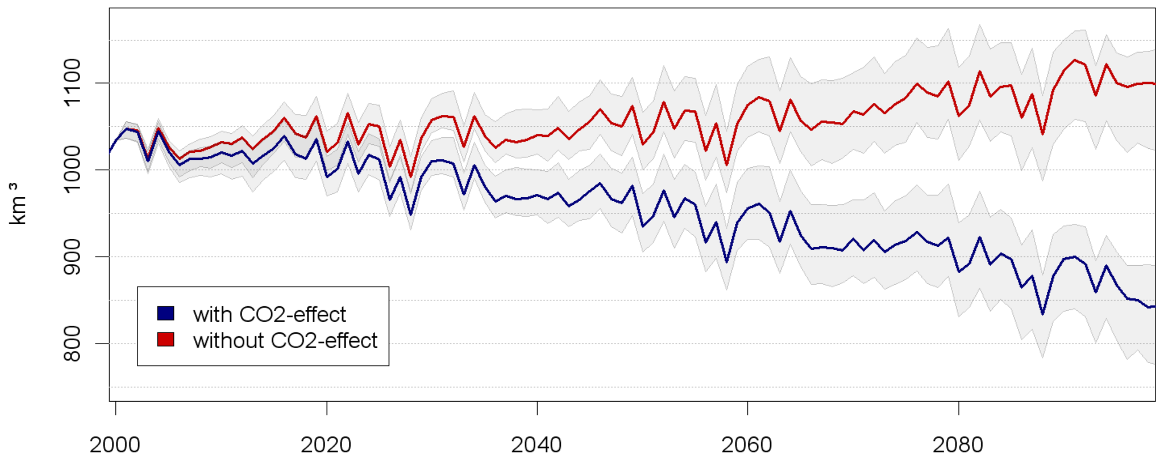


Fig. 6: LPJmL-simulated total global NIR (km^3) for the years 2000 to 2099, portrayed as the median across the 19 GCMs (coloured lines) and the spread among the GCMs (grey areas). NIR is shown both for the standard simulation (blue) and for a simulation in which atmospheric CO_2 concentration was held constant at the year 2000 level (red), in order to highlight the beneficial effect of increased CO_2 concentration on the crops.

This evidence might leap to the conclusion that in many regions NIR is likely to decrease and that climate change thus will have a positive overall effect. However, such a conclusion would be misleading for the following reasons.

- First, the beneficial CO_2 effect can only be realised if other factors are not limiting. While water limitation is considered by the LPJmL model, nutrient limitation is not explicitly accounted for, such that the effect is overrated in those regions where nutrient limitation will occur in the future. In other words, the CO_2 effect is unlikely to materialise in poorly managed agricultural/irrigation systems with low soil quality and low fertiliser input, such that the present results already imply an adaptive shift in crop management.

- Second, a number of regions are still likely to face an increase in NIR (see red-coloured areas in Figs. 4, 5) if CO_2 effects were considered.

- Third, even if the CO_2 effects would be at the optimum end demonstrated here, a large portion of the water needed to fulfil the irrigation requirements will have to be extracted from non-renewable and non-local water resources. This is problematic also in regions where NIR and its non-renewable fraction will decline, as still large amounts of water will be required year by year. Our estimate is that presently about 30% (828 $km^3\ yr^{-1}$) of the gross irrigation requirements are taken from non-renewable and/or allochthonous water resources (i.e. mostly from fossil groundwater and from diverted rivers), and that this amount will cumulatively increase till the 2080s by ~35 $km^3\ yr^{-1}$ (ensemble median without CO_2 effect). In the simulation with CO_2 effect, the non-renewable fraction is simulated to decrease globally by ~150 $km^3\ yr^{-1}$ compared to the present, but this still implies substantial withdrawals from non-renewable resources (as mentioned above) – while it is an open question whether these amounts will be available at all.

- And fourth, any changes in population numbers and lifestyles, thus changes in (irrigated) crop areas and related changes in water demand, are not accounted for in this study. Since population is projected to increase strongly in many regions (including countries that presently depend to a large degree on irrigation), these developments are very likely to increase global and regional NIR, possibly outdoing any positive effects of climate and CO_2 change. However, increases in irrigation efficiency, which is presently rather low in many regions (Rohwer et al. 2007), could substantially ease this situation, e.g. by shifts to micro-irrigation systems with little evaporative and seepage water losses on the way to the field.

Notwithstanding the fact that these processes and potentials were not considered in the present analysis, it provides a comprehensive assessment of climate change effects on present irrigation areas: For the first time, the full range of 19 GCMs has been explored to quantify these impacts, and the large uncertainty among the GCMs (especially in terms of precipitation projections) has been demonstrated. Also, we explicitly accounted for the effects of CO_2 rise on plant growth and water productivity – these turned out to be beneficial, but only if proper crop management will enable their realisation in the field and if unsustainable water resources will no longer be exploited. Further research accounting not only for climate impacts on existing irrigation areas but also for potentials to expand irrigated and rainfed cropland, to increase crop production by soil conservation and water harvesting (as explored globally in Rost et al. 2009) and to improve irrigation efficiencies is urgently needed, in order to explore sustainable water management pathways that meet the growing food and water demand of an increasing world population.

3 Impacts of anthropogenic and climate change on water availability for irrigation

In the first section it was shown that irrigation has and will continue to have strong effects on climate change. Furthermore, as shown in section 2, changes in climate will have a strong impact on the irrigation water requirements. A third important question is where irrigation will take place in the future and whether available water resources will be sufficient to meet these future requirements. In order to answer that question, first a WATCH study was performed (WBs 1 and 6) to estimate the importance of the role of reservoirs in the current irrigation system. Results showed that around 2650 km^3 withdrawals are annually required for irrigation, 1250 km^3 of which can be extracted from rivers and lakes directly, 460 km^3 is taken from artificial (human build) reservoirs and 940 km^3 is needed from other unspecified sources that can either be groundwater, inter-basin transfers, desalination processes or might also be partly unavailable (Biemans et al., 2011). However, the role of reservoirs in the supply of irrigation water differs enormously between basins (Fig. 7).

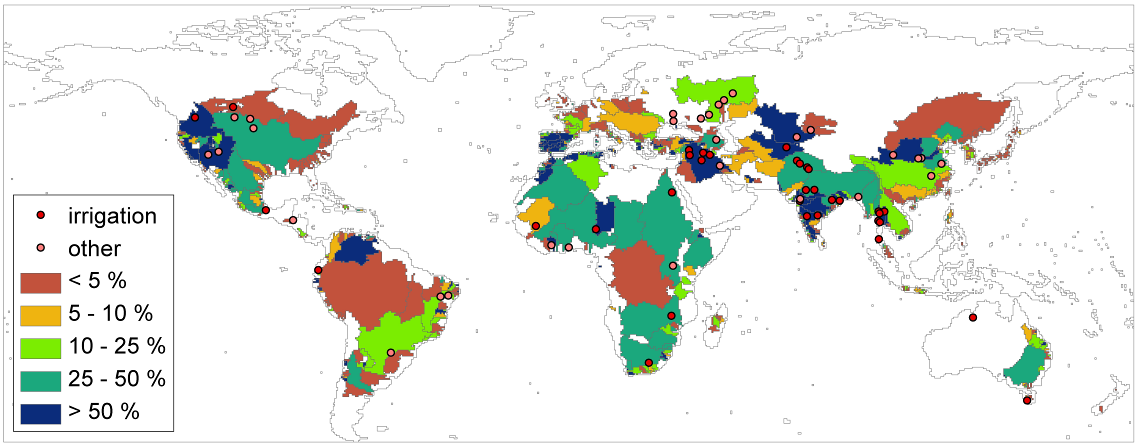


Fig. 7: LPJmL-simulated contributions of reservoirs to total irrigation water supply (average over 1981-2000). Colours represent the percentage of extra water that was irrigated in the simulation with reservoirs included compared to a simulation without reservoirs for the period 1981-2000. The dots represent all reservoirs >5 km^3 from which irrigation water is supplied: in red the irrigation reservoirs, in pink those primarily built for other purposes, but supplying irrigation water.

Siebert et al. (2010) estimated the global consumptive groundwater use for irrigation to be 545 km^3 yr^{-1}. This number is not very different from the 940 km^3 found by Biemans et al. (2011), as the difference between the consumption and the withdrawal reflects the inefficiency of the irrigation system which has large regional differences, but averages around 50% globally (Rohwer et al., 2007). A combination of the analysis of Siebert et al. (2010) and Biemans et al. (2011) shows that 90% of the current irrigation withdrawal can be fulfilled by the available resources (Fig. 8).

It is largely unknown how this situation will change in the future. Recent studies show that extractions of groundwater have already led to declining water tables in several regions (Rodell et al., 2009; Wada et al., 2010). Therefore, it is unlikely that groundwater extractions can continue in the future at present rates. Furthermore, with a growing population that is getting richer, global food production will have to increase, amongst other methods by the expansion of cropping areas leading to an increasing water demand. The future water-related risk to food security can only be assessed in an integrated framework including a fully coupled global crop and water resources model, accounting for the combined effect of both climate change and changes in food demand and related land use change (Biemans et al., in preparation).

For a WATCH WB2 study, IIASA developed scenarios for the future global food system based on their GAEZ model and methodology (e.g. Fischer et al., 2005; 2007). For the A2 scenario an increase in the total global rainfed (+14%) and irrigated cropping area (+44%) is projected (2100 with respect to 2000). For B1, these numbers are -4% and +31%, respectively. The effect of these land use changes on the total water demanded for irrigation in 2100 is estimated here using the LPJmL model (Rost et al., 2008) including the effect of climate change by forcing the model with the scenarios developed within WATCH WB1 (Weedon et al., in press).

Subsequently the potential contribution of different sources to fulfil this water demand is calculated. From Fig. 8 it can be concluded that under current conditions, 90% of the total irrigation withdrawal demand could be met by available resources. However this fraction may decrease in the future to only 74% (A2 2100) or 79% (B1), meaning that one fifth to one fourth of the total water required for irrigation cannot be met even under the positive assumption that groundwater extractions will continue at current volumes.

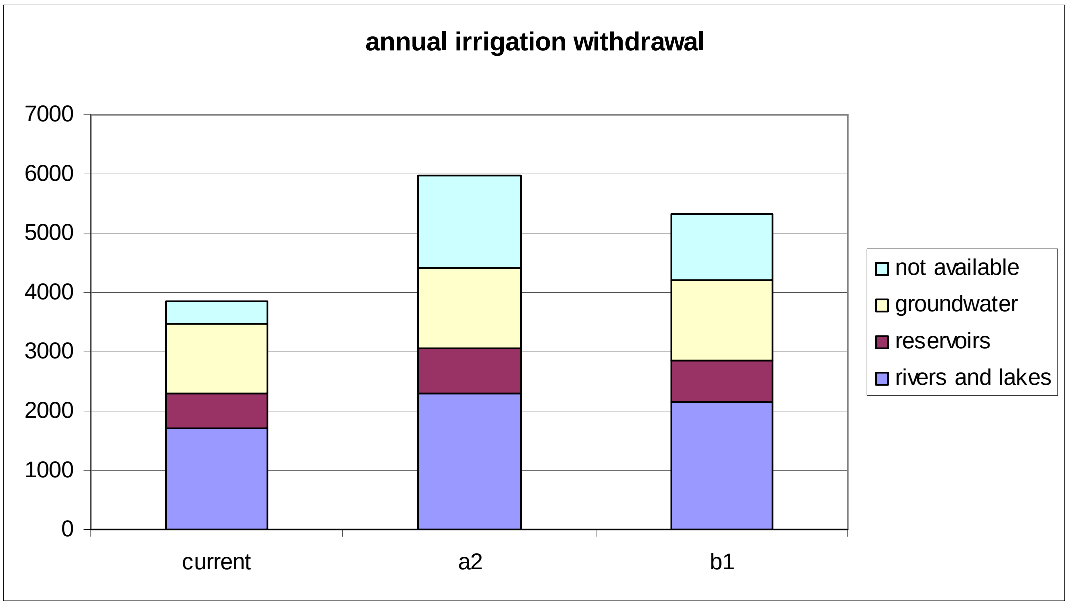


Fig. 8: Total withdrawal demand ($km^3\ yr^{-1}$) and differentiation to different sources of supply for current and future (A2 and B1) climate and land use. **(*Preliminary figure based on research in progress – do not cite.*)**

Inevitably, this water shortage will have an effect on the total global crop production, as is shown in Fig. 9. Analysis of the modelling results show that under current conditions, approximately 3% of the total annual crop production (rainfed and irrigated) is lost because of limited water supply. This number could increase to 10-18% (A2) or 8-17% (B1) in 2100, depending on the availability of groundwater.

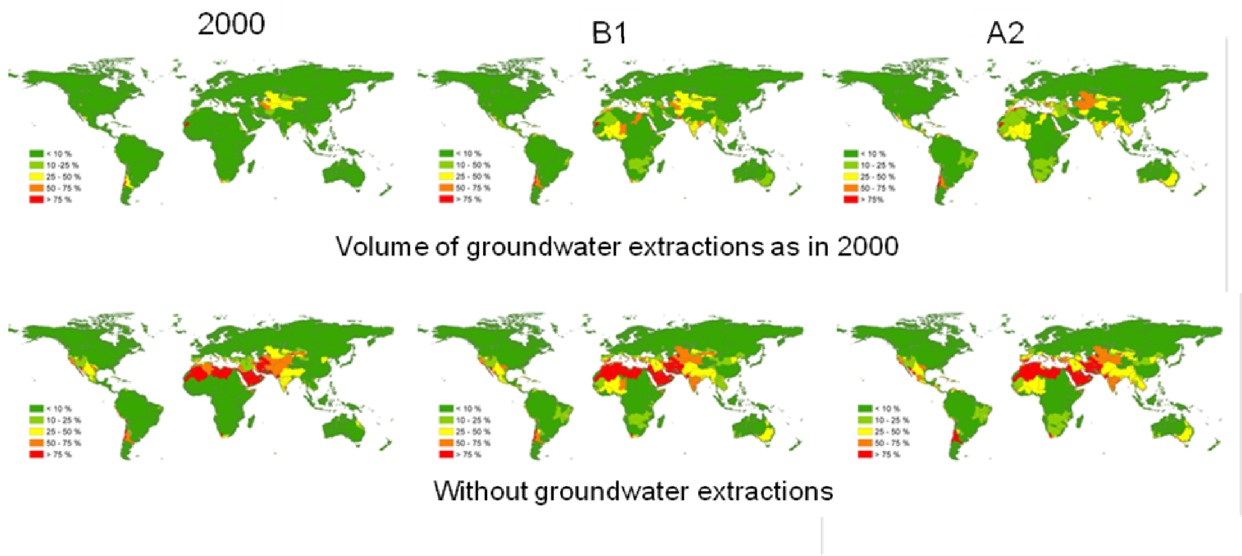


Fig. 8: Percentage of crop losses caused by unmet irrigation water demands under current conditions, and under B1 and A2 climate change and land use change scenarios around 2100, with (upper panels) and without (lower panels) supply from groundwater. **(*Preliminary figure based on research in progress – do not cite.*)**

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