Agricultural Water Use under Climate Change: A Global Assessment

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Abstract

Agriculture is by far the largest consumer of water globally, accounting for approximately 70 percent of global water withdrawals and 90 percent of total water consumption. Irrigated agricultural land comprises less than 20 percent of total cropland but produces nearly 40 percent of the world's food. With growing population and income in the coming decades, additional demands for irrigation due to higher food demands as well as intensified inter-sectoral competition for water are expected for many places around the world. Climate change further complicates the situation as precipitation patterns and hydrological regimes are altered and potential evapotranspiration of crops will increase as a result of higher temperature. It is essential for water managers and policy makers to proactively address growing water challenges. To better understand future water demand and supply under global change, and especially for agriculture, the largest water user, we simulate sectoral water demand and supply out to 2050 for 281 water use units, which are intersections of large river basins and administrative units, using various climate scenarios. The analytical model used for the analysis is IMPACT, a global water and food projections model developed at the International Food Policy Research Institute, which includes a semi-distributed global hydrological module and a water management simulation module, in addition to the global agricultural trade module. Changes in water availability changes and irrigation water supply reliability are presented for the world's regions.

Key words: Climate change, irrigation, consumptive use

Introduction

The world has witnessed dramatic increase of irrigation in the past century. Irrigated area has increased from 50 million hectares (mha) in 1900 to almost 280 mha at present. Today, agriculture is the largest user of water, accounting for approximately 70 percent of global water withdrawals and 90 percent of consumptive water use.

Irrigation has played an important role in increasing agricultural production worldwide. Crops under irrigation cover less than 20 percent of the world's cropland but contribute 40 percent of global food production (Molden 2007). Without irrigation, it would not have been possible to achieve the remarkable agricultural production growth, marked by the "green revolution" (Evenson and Gollin 2003), to support rapid population growth in the world over the past half century. Moreover, irrigation systems often serve many other rural water uses, including rural domestic water supplies, household gardens, livestock, fishing, recreation, and other enterprises (Meinzen-Dick 1997; Bakker et al. 1999). Irrigation also has multiplier effects for non-agricultural and urban areas and thus makes further contributions to the overall economy (Bhattarai et al. 2007; Strzepek et al. 2008).

Nevertheless, in many regions around the world, irrigation is the main contributor of water scarcity. Growing water scarcity has become prevalent in important agricultural areas, such as declining water tables in Northern India, Pakistan, Northern China, and the Ogallala aquifer in the United States, as well as dried-up rivers such as the Yellow River in China, the Krishna in India, Syr Darya in Central Asia, all of which experienced no discharge to the sea for extended periods of time. In addition, since food security is so closely connected to water availability and irrigation in many regions, conflicts over water are increasing in number and intensity (Maclean and Voss, 1996). This evidence of growing water scarcity poses challenges to the sustainability of irrigation and future food security in such regions and globally.

Although water stress is already high under present climate variability, climate change may further complicate the situation, through its regionally differing effects on water availability and a general increase of agricultural water requirements everywhere, under global warming. According to the IPCC the immediate impact of climate change will be on water resources, manifested by change in rainfall patterns and severe hydro-climatic extreme events including extended periods of droughts (Kundzewicz et al. 2007). Agricultural water use is therefore expected to be strongly affected due to expected changes in drivers on both the supply and demand side.

To cope with the challenges posed by climate change on agricultural water use, policy makers and development donor agencies need to understand the potential impacts of climate change at the scale relevant to their decision-making. At global and continental scales, an increasing number of studies focus on climate change impacts on water availability (Arnell 1999; Arnell 2003; Arnell 2004; Milly 2005) or irrigation requirements (Doll and Siebert 2002a; Doll 2002b) while few studies have examined combined water availability and irrigation impacts. This paper explores the potential impacts of climate change on agricultural water use.

Drivers of Agricultural Water Use

Agricultural water use is primarily driven by irrigation water requirements, which are determined by irrigated areas, cropping intensity, crop types, varieties, and irrigation efficiency at the “horizontal” or land dimension, and rainfall and potential evapotranspiration at the “vertical” or atmosphere dimension. Virtually, net irrigation requirement (NIR) of a crop equals the crop area multiplied by the maximum evapotranspiration of the crop, ETMc, less effective rainfall. For an area with multiple crops the total net irrigation requirement (TNIR) is the sum of that for all crops, namely:

$$TNIR = \sum_t \sum_c A_c \cdot NIR_{c,t}$$

where

$$NIR_{c,t} = \begin{cases} ETM_{c,t} - PE_{c,t}, & ETM_{c,t} > PE_{c,t} \\ 0, & ETM_{c,t} > PE_{c,t} \end{cases}$$

In the above equation *t* represents crop growing stage, *c* denotes crop, *ETM* is maximum evapotranspiration and *PE* is effective rainfall. In a river basin context, the gross consumptive irrigation requirement is equivalent to *TNIR* divided by basin irrigation efficiency (Keller and Keller 1995; Rosegrant et al. 2002).

Although irrigation water requirement is the main driver of agricultural water use, actual irrigation demand is also affected by policy or institutional settings that affect water demand such as water price and water rights. In addition, planted irrigated area and crop mix are usually heavily influenced by international crop commodity prices.

On the supply side, actual agricultural water use is constrained by water resources defined by local or regional hydrology and its accessibility determined by water infrastructure, management and policy. We categorize the demand and supply side drivers of agricultural water use as follows.

Demand Side Factors

1. Socioeconomic factors. Population growth, economic growth and associated dietary changes are key socioeconomic factors that drive food demand and consequently agricultural water use. The global population is expected to reach 9.2 billion by 2050, 86 percent of whom will live in less-developed countries and 70 percent in rapidly growing urban areas (Rosegrant et al. 2009). Increased wealth and higher purchasing power will lead to higher consumption and a greater demand for processed food and animal products (Godfray et al. 2010). Diets based on livestock products, sugar, and oil typically require more water to produce than those based on staple crops. Crops fed to cattle already account for around 18 percent of the total crop water consumption today, a share expected to grow over the next two decades.

   Population and economic growth also result in increased water demand from the domestic and industrial sectors and, in many regions, increased appreciation for environmental services of water, including ecological and environmental flows. These sectors will compete with agriculture for water, and will likely require transfer of water out of agriculture (Rosegrant and Ringler 1998).

2. Policy, Institutional and Regulatory Changes. Future changes in water and agricultural policies, institutional arrangements and regulations play an important role in the trend of agricultural water use. Generally, policies outside the water sector impact water use availability in agriculture more than direct water use policies (see also Ringler et al. 2010).

Supply Side Factors

1. Changes in Irrigation Technology and Agricultural Management Practices. Adoption of water-saving irrigation technologies or agricultural water management practices may increase water use efficiency, thus reduce irrigation water requirements. As the largest water user in the world, agriculture has the greatest water-saving potential. Irrigation technologies with higher efficiencies are expected to be increasingly adopted by farmers, when such technologies are suitable, as water becomes scarcer and farmers' affordability and willingness-to-pay increases. Higher energy costs will likely also further induce water savings in agriculture. However, highly-efficient technologies at the farm field scale do not always save water in a river basin context. Policies created to encourage water saving technology adoption should focus on areas where field level water savings can result in increased water availability (Blanke et al. 2007). Besides irrigation technology, improved soil and water conservation technology and agricultural water management practices, such as alternative wet and dry irrigation of rice, can also lead to water-saving.

2. Change in irrigation investment. As irrigated cereal yields are 60 percent higher, on average, than rain-fed yields, strategies for yield improvements often focus on how to improve or expand access to water for agriculture (Rosegrant et al. 2009). While irrigation expansion is expected to significantly increase crop production, it requires large amounts of freshwater that are not (readily) available everywhere. Limited development of water resources in some parts of the world, such as Sub-Saharan Africa, and growing physical water scarcity in other parts, such as the Middle East and North Africa, are direct constraints to irrigation expansion. Asia contributes slightly more than 60 percent of the world's total irrigated area; however, massive expansion of irrigated agriculture in that region has largely ended (Svendsen and Rosegrant, 1994). In Asia, the priority is efficiency improvement. For SSA, where irrigation potential is largely untapped, we expect irrigation expansion to secure future food supply and reduce poverty. In the era of climate change, irrigated agriculture is expected to produce a greater share of the world's food in the future, as it is more resilient to climate change in all but the most water-scarce basins (Molden 2007).

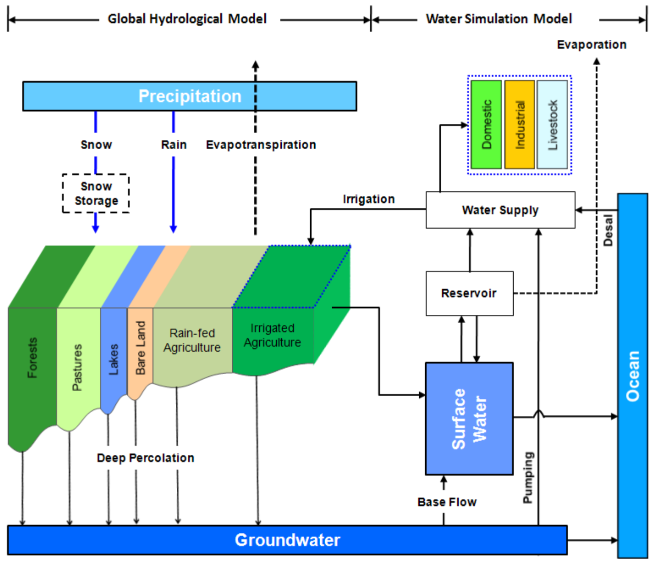
3. Climate change. Climate change affects both the supply and demand sides of irrigation through its impacts on water availability and crop evapotranspiration requirements. This driving factor of agricultural water use is the focus of this paper.

Linked Global Modeling System of Water Availability and Use

Assessing climate change impacts in the water sector requires analytical models to quantitatively evaluate water availability and allocation under historical and future climate conditions. We use a linked modeling system that consists of a semi-distributed Global Hydrological Model (IGHM) (Zhu et al. 2010) and the Water Simulation Model (IWSM) of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) developed at IFPRI (Rosegrant et al. 2002). Both the IGHM and the IWSM cover global river basins for which we analyze the impacts of climate change on water availability and use. Although the IWSM simulates all major water use sectors, the focus of this study is to evaluate the implications of climate change on irrigation water supply caused by changes of river basin hydrology and irrigation water requirements under climate change.

Figure 2 illustrates the structure of the linked modeling system. In a river basin, the IGHM hydrological model simulates the rainfall-runoff process taking into account land cover classes in computing potential evapotranspiration. The IWSM water use simulation model simulates reservoir regulation of natural flow and abstraction of groundwater according to estimated total water demand consisting of domestic, industrial, livestock and irrigation sectors. The IWSM uses monthly total runoff and potential evapotranspiration calculated in the IGHM to simulate water management and allocation. On top of Figure 2, the double headed arrows define the functional boundaries of these two models. In the next sections we describe in more detail the IGHM and the IWSM models.

Figure 1: Structures of and linkage between the **s**emi-distributed hydrological model and water simulation model



Semi-distributed Global Hydrological Model

The hydrological model IGHM is a semidistributed parsimonious model. It simulates monthly soil moisture balance, evapotranspiration and runoff generation on each 30 arc minute grid cell spanning over the global land surface except the Antarctic. Gridded output on hydrological fluxes, namely evapotranspiration and runoff, are spatially aggregated to food production units (FPU) within the river basin, weighted by grid cell areas, and then incorporated into the WSM (Zhu et al. 2010).

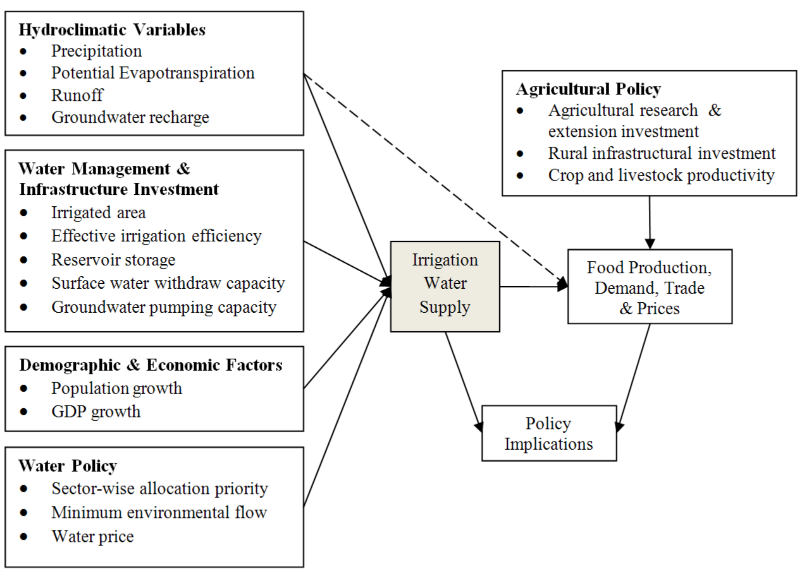
Comparisons of simulated and observed flow series indicate that the IGHM can simulate monthly runoff reasonably well, and model performance in the validation period is nearly as good as that in the validation period. This is further confirmed by the Nash-Sutcliffe model efficiency values in the calibration period and validation period for major river basins.

Water Simulation Model

The IWSM of IMPACT simulates water demand, supply, reservoir storage regulation, and surface and ground water withdraw at monthly time period, using food production unit, usually a basin or sub-basin, as the fundamental unit of depletion accounting. Using the lumped unit avoids tracking detailed water use process as river basin management models do. When the scale of analysis goes from basin down to irrigation system and then to field scale water flow pathways become increasingly complex and consequently water balance calculation for depletion accounting quickly becomes not tractable if the geographic domain of analysis is not compromised. In addition, sophisticated water accounting relies on extensive flow measurement which is almost impossible for a global water model like the IWSM.

The IWSM optimizes water supply according to demand, driven by several kinds of factors, as shown in Figure 2. The hydroclimatic factors include long-term monthly precipitation, potential evapotranspiration, and internal renewable water resources; the demographic and economic factors are population and GDP growth rates that drive the growth of domestic and industrial water demand; the water management and infrastructure investment factors include projected irrigated area growth, changing rate of effective irrigation efficiency (Keller and Keller 1995), reservoir storage increase, the changes in surface and ground water withdraw capacities; and policy and institutional parameters including water allocation priorities.

Figure 2: Driving force in the Water Simulation Model and its linkage with the IMPACT agricultural production, demand and trade model



In optimizing water supply, the IWSM firstly calculates total water supply for every month, and then allocates the total supply to sectors on a priority-based manner. It assumes domestic water demand is the first priority, industrial and livestock demand is the second priority, and the remaining water is available for irritation. Total irrigation water supply is further allocated to crops according to crop water requirements. Flow regulation by surface storage, diversion of surface water to users and groundwater pumping are constrained by their capacities which are assumed to grow over time. Minimum environmental flow requirement is treated as a hard constraint in the model.

Thus, the IWSM focuses on the waters that can be managed – streamflow and groundwater, also referred to as “blue water”, and for few cases, sea water desalinization. The portion of crop-evapotranspirated water from rain or snow, namely “effective rainfall”, is considered in estimating irrigation water requirement. In this modeling framework and at this scale, whether irrigation is based on surface or renewable groundwater has limited relevance, since consumptive groundwater use is equivalent to transforming blue low flow recharge to green water flow (Falkenmark and Lannerstad, 2005).

The IWSM simulates water balance at FPU scale out to 2050. Large rivers across multiple FPUs are connected by their relative upstream-downstream relationship, with the outflow from an upstream FPU being the inflow of the immediate downstream FPU. Climate change impacts are channelized to irrigation and crop production in the IMPACT model through changes taken place in the hydrological cycle, including precipitation, runoff and crop-specific potential evapotranspiration.

Data and Scenarios

Climate Change Scenarios

Four climate change scenarios for 2050 are used in this study, based on statistical downscaling conducted by Jones et al. (2009) that used GCM simulations available from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. The eight chosen climate scenarios are based on climate projections of four GCMs, namely CNRM-CM3, CSIRO-Mk3.0, MIROC 3.2 (medium resolution), and ECHam5 forced by a medium-emission scenario SRES A1b (IPCC, 2000). For convenience, we call these scenarios, respectively, CNRM, CSIRO, MIROC, and ECHam, which are all forced by SRES A1b emissions. Appendix A provides a more detailed description of the GCMs.

We calculated the gridded mean monthly changes of precipitation and temperature between a historical period and a future period centered at 2050 from the downscaled climate dataset of Jones et al. (2009), and then apply them to the historical monthly precipitation and temperature series of 1970-2000 from the CRU TS2.1 global climate database developed by Mitchell and Jones (2005). The 1970-2000 series CRU data is regarded as baseline or climate normal in this paper. For precipitation, the relative changes are used to multiply the 1970-2000 CRU precipitation as multipliers. For temperature, the absolute mean monthly changes derived from Jones et al. (2009) are added upon 1970-2000 CRU temperature monthly series. The baseline climate data and the constructed climate change scenarios data are used by the IGHM hydrological model to simulate the responses of evapotranspiration and water availability under the baseline and the four climate change scenarios. Although the IGHM runs for the entire 1970-2000 period, only the hydrological output for 1971-2000 is used by the IWSM model to analyze water demand and supply. The 12 months in year 1970 is spinning-up period in the hydrological model for establishing a reasonable initial condition for the following year.

Economic and Demographic Scenarios

The water use model IWSM uses the 2008 UN medium variant population projection, and country-level GDP growth rates developed by IFPRI and the World Bank, with updates for Sub-Saharan Africa and South Asian countries. These projections were also applied in Nelson et al. (2010).

Irrigation Scenarios

Estimated changes in gross irrigated areas and basin efficiency improvement over the period 2010-2050 are shown in Table 1. Changes in gross irrigated area reflect changes in both net irrigated area and cropping intensity.

Globally, we assume only a slight increase in irrigated area during 2010-2050. Irrigated area in developed countries decreases by approximately 3 mha, which is compensated by the increase of roughly the same amount in developing countries. Continent-wise, both the North America and Europe (NAE) region and the East-South Asia and Pacific (ESAP) region experience irrigated area contraction, by 2.7 mha and 2.6 mha respectively, representing a 4.6 percent and 1.1 percent reduction from their 2010 values. The Central West Asia and North Africa (CWANA) region experiences a small decline in area. Expansion of irrigated areas are expected for the Latin America and Carrabin (LAC) region and the Sub-Saharan Africa (SSA) region, with an increase of about three mha in each region, representing a 21.2 and 62.2 percent increase from their 2010 values. This irrigated area change scenario represent an optimistic view that future food supply can be satisfied without major expansion of irrigation.

Table 1: Change of gross irrigated areas and basin efficiency during 2010-2050

Region	Gross irrigated area			Basin efficiency		
	2010	2050	Change (%)	2010	2050	Change
NAE	58.4	55.7	-4.6	0.63	0.67	0.04
ESAP	236.4	233.8	-1.1	0.57	0.64	0.07
CWANA	46.9	46.2	-1.4	0.59	0.63	0.04
LAC	14.4	17.5	21.6	0.47	0.54	0.07
SSA	5.0	8.1	62.2	0.50	0.56	0.07
Developed	56.2	53.1	-5.5	0.64	0.67	0.03
Developing	305.0	308.3	1.1	0.57	0.63	0.07
World	361.1	361.4	0.1	0.58	0.64	0.06

Note: NAE - North America and Europe; ESAP - East-South Asia and Pacific; CWANA - Central West Asia and North Africa; LAC - Latin America and Carrabin; SSA - Sub-Saharan Africa.

Basin efficiency is expected to increase in all regions, though the magnitudes of change differ. The world experience an average increase of basin efficiency, from 0.58 in 2010 to 0.64 in 2050. The developing world is expected to have large increase of basin efficiency than the developed world.

Results

The IGHM and IWSM model runs provide water availability and water use results for climate normal and each of the four climate change scenarios presented in the following sections.

Water Availability under Climate Change

Annual average internal renewable water resource (IRW) is computed from 30-year monthly runoff series simulated by IGHM, for each scenario, as shown in Table 2. Globally, climate change increases IRW under all scenarios. The largest increase, 7 percent, takes place under MIROC, while the smallest increase, 1 percent, takes place under CSIRO. Total IRW in the developed countries is expected to increase more than in the developing countries, for all scenarios except the CNRM.

At the continental scale, the impacts on IRW differ significantly across scenarios. For instance, both the CNRM and MIROC scenarios project large increase of IRW in the CWANA region, however the ECHAM scenario project a four percent decrease by 2050. For the other regions, all scenarios project IRW increase for the NAE and ESAP regions, ranging between 3.3 and 12.4 percent for NAE and between 2.4 and 18.1 percent for ESAP. IRW in the LAC region is projected to increase slightly except for the MIROC scenario that project a 3.6 percent decrease. The SSA is projected to have a more than seven percent increase by of IRW under CNRM and MIROC, a one percent increase under ECHAM and a 3.5 percent reduction under CSIRO.

Table 2: Internal renewable water resources (IRW) under climate normal (NoCC) and climate change scenarios for 2050, and percent changes of IRW between NoCC and 2050 climate change

	Region	NoCC	CNRM	CSIRO	ECHAM	MIROC
Internal Renewable Water Resource (km^3/yr)	NAE	7314	7610	7553	8222	7906
	ESAP	12631	13272	12940	13819	14917
	CWANA	656	898	683	627	806
	LAC	14935	15225	14951	14961	14398
	SSA	4285	4608	4133	4333	4588
	Developed	8497	8860	8838	9510	9465
	Developing	31324	32753	31421	32452	33150
	World	39821	41613	40259	41962	42615
Change from NoCC (%)	NAE	-	4.0	3.3	12.4	8.1
	ESAP	-	5.1	2.4	9.4	18.1
	CWANA	-	37.0	4.1	-4.3	22.9
	LAC	-	1.9	0.1	0.2	-3.6
	SSA	-	7.5	-3.5	1.1	7.1
	Developed		4.3	4.0	11.9	11.4
	Developing		4.6	0.3	3.6	5.8
	World		4.5	1.1	5.4	7.0

Note: NAE - North America and Europe; ESAP - East-South Asia and Pacific; CWANA - Central West Asia and North Africa; LAC - Latin America and Carrabin; SSA - Sub-Saharan Africa.

Irrigation Water Supply Reliability at Global and Continental Scales

Irrigation water supply reliability (IWSR) is defined as the ratio of water supplied for irrigation to the water requirement of irrigation at an annual basis. It is an indicator reflecting the level of reliability of irrigation water supply relative to requirement, in terms of annual total water volumes. Table 3 presents IWSR in 2010 and 2050 under climate normal and in 2050 under the four climate change scenarios.

In general, the developed world has a higher IWSR than the developing world at present, and is expected to remain so until 2050. This can be partially explained by the fact that irrigation infrastructure is relatively better developed and managed in the group of developed countries.

Regionally, IWSR in the NAE, LAC and SSA regions are much higher than in CWANA and ESAP. ESAP has the largest irrigated areas among all regions and its water availability and use are strongly influenced by Asian monsoon. The irrigation potential of SSA is yet to be further explored. So far its irrigated area accounts for barely 5-6 percent of the world's total. The LAC region is water abundant in general, although there are local differences in availability with the heavily populated coastal regions often experiencing water scarcity (Chilean and Peruvian coast, for example).

The developed world, in general, sees an increase in IWSR during the period 2010-2050 under climate normal, due to improvement of basin efficiency and a decrease of irrigated areas, in addition to relatively slow or flattened non-agricultural water use trends. An increase in IWSR is also found for the developing countries overall, despite the slight increase in irrigated areas. This is exclusively due to the increase in basin efficiency, given that non-agricultural water uses, notably domestic and industrial sectors, increase dramatically during 2010-2050 in the developing world.

Table 3: Irrigation water supply reliability under climate normal in 2010 and 2050 and under climate change scenarios in 2050

Region	2010	2050				
	NoCC	NoCC	CNRM	CSIRO	ECHAM	MIROC
NAE	0.86	0.89	0.88	0.88	0.88	0.88
ESAP	0.74	0.78	0.80	0.76	0.77	0.84
CWANA	0.55	0.55	0.63	0.56	0.52	0.57
LAC	0.95	0.96	0.94	0.96	0.96	0.95
SSA	0.87	0.89	0.88	0.89	0.88	0.89

Developed	0.92	0.95	0.94	0.95	0.94	0.94
Developing	0.71	0.75	0.77	0.74	0.73	0.78
World	0.73	0.77	0.79	0.76	0.75	0.80

Note: NAE - North America and Europe; ESAP - East-South Asia and Pacific; CWANA - Central West Asia and North Africa; LAC - Latin America and Carrabin; SSA - Sub-Saharan Africa.

We compare the IWSR levels in 2050 under climate normal and climate change scenarios, to infer the impacts of climate change on irrigation water use. At global and regional scopes, the impacts seem small, as a result of spatial aggregation. The developed world generally sees no change or a slight decrease of IWSR under climate change, depending on scenario. The developing world sees relatively small increases in IWSR under the CNRM and MIROC scenarios, and slight decrease under the CSIRO and ECHAM scenarios. Globally, IWSR is highest under MIROC and lowest under ECHAM.

Regionally, we found more pronounced and diversified changes in IWSR under different climate change scenarios. For instance, the IWSR of ESAP is projected to decrease under CSIRO but increase notably under MIROC. The CWANA region is projected to have a much larger IWSR under CNRM but a much lower IWSR under ECHAM. The ESAP region sees slight decrease of IWSR under CSIRO but a fairly large increase under MIROC. The IWSR of NAE sees little change from climate normal and the IWSR values across scenarios are close.

Conclusions

We analyzed the hydrological and agricultural water use impacts of climate change at the global and continental scales. The analysis used downscaled climate forcing data for four scenarios and estimated trends of future economic and demographic growth as well as changes in basin irrigation efficiency and irrigated areas. Climate change impacts on water availability and irrigation water supply reliability are presented in this paper. These results are scenario-dependent and regionally different.

We set up a framework for agricultural water use assessment under climate change at global and continental scales. However, high uncertainty remains regarding climate change impacts on agricultural water use, owing to uncertainties embedded in the data and projections used in the analysis, including but not limited to future demographic and economic growth, irrigated area expansion and distribution, in addition to climate change scenarios.

Appendix A: GCMs used in this Analysis

Table A-1 lists the research centers that developed the GCMs used in this analysis.

Table A-4: List of research organizations where the GCMs are developed

GCM Model	Institute
CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques, France
CSIRO-Mk3.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) Atmospheric Research, Australia
ECHam5	Max Planck Institute for Meteorology, Germany
MIROC 3.2, medium resolution	Center for Climate System Research, University of Tokyo; National Institute for Environmental Studies; and Frontier Research Center for Global Change (JAMSTEC), Japan

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