IMPACT OF CLIMATE CHANGE AND VARIABILITY ON IRRIGATION REQUIREMENTS: A GLOBAL PERSPECTIVE

PETRA DÖLL

Center for Environmental Systems Research, University of Kassel, Kurt-Wolters-Str. 3, D-34109 Kassel, Germany
E-mail: doell@usf.uni-kassel.de

Abstract. Anthropogenic climate change does not only affect water resources but also water demand. Future water and food security will depend, among other factors, on the impact of climate change on water demand for irrigation. Using a recently developed global irrigation model, with a spatial resolution of 0.5° by 0.5°, we present the first global analysis of the impact of climate change and climate variability on irrigation water requirements. We compute how long-term average irrigation requirements might change under the climatic conditions of the 2020s and the 2070s, as provided by two climate models, and relate these changes to the variations in irrigation requirements caused by long-term and interannual climate variability in the 20th century. Two-thirds of the global area equipped for irrigation in 1995 will possibly suffer from increased water requirements, and on up to half of the total area (depending on the measure of variability), the negative impact of climate change is more significant than that of climate variability.

1. Introduction

Anthropogenic climate change not only affects runoff and thus water availability but also the demand for water. If a region becomes drier and warmer, the decreased water availability will be exacerbated by an increased water demand. The water use sector that will be influenced most by climate change is irrigation. Irrigation is by far the largest use sector; today about 67% of the current global water withdrawal and 87% of the consumptive water use (withdrawal minus return flow) is for irrigation purposes (Shiklomanov, 1997). Irrigated agricultural land comprises less than one-fifth of the total cropped area but produces about two-fifths of the world's food. It is generally expected that irrigated agriculture will have to be extended in the future in order to feed the world's growing population. However, it is not yet known whether there will be enough water available for the necessary extension. One step towards evaluating how much water will be needed for irrigation in the future is to quantify how climate change will affect irrigation water requirements (*IR* – the amount of water that must be applied to the crop by irrigation in order to achieve optimal crop growth). In the next step, the estimated impact of climate change on the plant-physiological water requirements could serve as input to a global agro-economic model which computes the economic demand for irrigation water by taking into account crop yields and prices, costs and water availability.

Climatic Change **54:** 269–293, 2002.

There are many studies on the impact of climate change on runoff, mostly at the river basin scale, but the impact of climate change on irrigation has rarely been explored. Adams et al. (1990) and Allen et al. (1991) used crop growth models for wheat, maize, soybean and alfalfa at typical sites in the USA and the output of two General Circulation Models (GCMs) to compute the change of *IR* under doubled CO_2 conditions. Results depend highly on the GCM; in three of the six agricultural regions defined by Adams et al., the GCM scenarios do not even agree on whether there is a decrease or an increase of water use. Allen et al. (1991) also computed a climate-driven change in growing periods, which highly influences *IR*. They concluded that the direct effect of increased CO_2 concentrations on crop transpiration and thus *IR* cannot be quantified yet because of insufficient knowledge about the various, often counteracting effects. (Decreased stomatal conductance decreases the transpiration, but increased leaf mass due to CO_2 fertilization and increased leaf temperature increase it.) Like other researchers (e.g., McCabe and Wolock, 1992; Ramirez and Finnerty, 1996), they performed a mere sensitivity analysis of the CO_2 effect and determined that any increases of *IR* due to climate change is moderated or even nullified by a decrease in bulk stomatal conductance; this depends also on the crop type. In their integrated economic assessment of climate change impacts on Egypt, Yates and Strzepek (1996) used the same crop models as Adams et al. and Allen et al. and also found that applying two different GCMs resulted in relevant differences in the predicted changes of *IR*. In addition, by using economic models, both Adams et al. and Yates and Strzepek computed the change of irrigated areas due to global climate change. To account for the high uncertainty of future climate, Jones (2000) constructed probabilities of temperature and precipitation change based on local and global climate scenarios and computed how often a certain irrigation requirement will be exceeded due to climate change; this procedure, however, was only applied to a single farm in Australia.

On the global scale, scenarios of future irrigation water use were developed by Seckler et al. (1997) and Alcamo et al. (2000). In both studies, the impact of climate change was not taken into account. In the work of Seckler et al., the smallest computational units were countries, while Alcamo et al. employed the raster-based global irrigation model GIM of Döll and Siebert (2001), with a spatial resolution of 0.5° by 0.5°.

In this paper, GIM is applied to explore the impact of climate change on the irrigation water requirements *IR* of those areas on the globe that were equipped for irrigation in 1995. Estimates of long-term average climate change for the 2020s and 2070s are taken from two different GCMs. In addition, the impact of climate change is compared to the impact of interannual and multidecadal climate variability in the 20th century. This gives an indication of the severity of the impact of climate change on *IR*. The comparison to the impact of interannual climate variability reflects the notion that farmers might not suffer much from climate change if the (long-term average) climate change impact is small compared to the impact of current climate variability, to which they are accustomed. The comparison to the impact of long-term climate variability in the 20th century shows whether the future changes of *IR* are more significant than the past climate-induced changes.

In our study, climate change is defined as changes in the long-term averages of precipitation and temperature only. Likely future changes in climate variability could not be taken into account as GCMs cannot provide reliable estimates of such changes. In our agro-climatological approach, climate change is assumed to modify the starting date of the growing season (but not its length) and, in a very simplified manner, the cropping pattern. Any change in size and location of the irrigated areas due to an adaptation to climate change or for any other reason is neglected. (Such changes could have been included, for example, by applying a global agro-economic model, which was beyond the scope of out research.) Furthermore, the direct effects of increased CO_2 concentrations on crop transpiration, in particular via a decreased bulk stomatal conductance, had to be ignored due to insufficient quantitative knowledge.

2. Global Model of Irrigation Requirements

The global model of irrigation requirements GIM (**G**lobal **I**rrigation **M**odel) of Döll and Siebert (2001) computes net and gross irrigation water requirements in all 0.5° by 0.5° raster cells with irrigated areas. ‘Gross irrigation requirement’ is the total amount of water that must be applied by irrigation such that evapotranspiration may occur at the potential rate and optimal crop productivity may be achieved. Only part of the applied water is actually ‘used’ by the plant and evapotranspirates; this amount, the difference between the potential evapotranspiration and the evapotranspiration that would occur without irrigation, is the ‘net irrigation requirement’. The other part of the added water serves to leach salts from the soil, leaks or evaporates unproductively from irrigation canals, or runs off; this amount depends on irrigation technology and management. The ratio of the net irrigation water requirement and the total amount of water that needs to be withdrawn from the source, the gross irrigation requirement, is called ‘irrigation water use efficiency’. Under conditions of restricted water availability, farmers may choose to irrigate at a lower than optimal rate. Then, the actual water withdrawal is less than the gross irrigation requirement, and, equally, the actual consumptive water use for irrigation is less than the net irrigation requirement IR_{net}.

GIM is a module of WaterGAP, a global model of water availability and water use that has been developed to assess the impact of global change on the problem of water scarcity (Döll et al., 1999). It is based on a global map of irrigated areas that shows the fraction of each 0.5° by 0.5° cell that was equipped for irrigation around 1995 (Döll and Siebert, 2000). On the global scale, there is little information about what crops are grown under irrigated conditions where and when. Therefore, only two crop types can be distinguished, rice and non-rice; the cropping patterns and the growing seasons are simulated by GIM, based on information about irrigated rice areas, cropping intensity, soil suitability and climate. IR_{net} per unit irrigated area is then computed as a function of climate and crop type, while the gross irrigation requirement is calculated by dividing IR_{net} by the irrigation water use efficiency.

2.1. GLOBAL MAP OF IRRIGATED AREAS

The digital global map of irrigated areas shows the irrigation density in 1995, i.e., the percentage of each 0.5° by 0.5° cell area that was equipped for controlled irrigation around 1995. Flood recession cropping areas and cultivated wetlands are not included in the map. The map was generated by combining information from large-scale maps, FAO data on total irrigated area per country in 1995 and, where available, national data on total irrigated area per county, drainage basin or federal state. The data base of the map is rather uncertain. In spite of the uncertainties, we consider the generated global map of irrigated areas to be appropriate for use in global and continental assessments. A discussion of the map quality as well as a description of the data sources and the map generation process can be found in Döll and Siebert (2000); the data set is available from the authors.

2.2. CROPPING PATTERN

The cropping pattern for each cell with irrigated land describes (1) whether only rice, only non-rice or both are irrigated there and (2) whether, within one year, there are one or two growing seasons for rice and non-rice. We assume that the growing period for both rice and non-rice is 150 days. The data used to model the cropping pattern are: total irrigated area, long-term average temperature and soil suitability for paddy rice (FAO, 1995) in each cell, harvested area of irrigated rice in each country (IRRI, 1988) and cropping intensity in each of 19 world regions (Table II). In general, 'cropping intensity' refers to the average number of crops that are consecutively grown within a year. In GIM, it refers to the average number of growing periods of 150 days duration each. If, for example, on one-half of the irrigated area of a world region, crops were grown only once a year, and on the other half two crops, one after the other, the average cropping intensity would be 1.5. The assumed cropping intensities are rough estimates which, however, strongly influence irrigation requirements.

2.3. GROWING SEASON

Once the cropping pattern of a cell is defined, the start date of each growing season is computed for each crop and growing season. Each moving 150-day period within a year is ranked according to its long-term average daily temperature and precipitation values (Döll and Siebert, 2001). The temperature criterion reflects that in each growing stage, rice and non-rice crops require a certain temperature range for optimum yield, while the precipitation criterion mirrors farmers' preference to start irrigated cropping during the wet season while harvesting is best done if it does not rain. The growing season is then defined to be the most highly ranked 150-day period; in case of two consecutive growing periods, the combination with the highest total number of ranking points is chosen.

2.4. NET IRRIGATION REQUIREMENT

Following the CROPWAT approach of Smith (1992), the net irrigation requirement per unit irrigated area during the growing season is computed, with a daily time step, as the difference between the crop-specific potential evapotranspiration and the effective precipitation as

$$\begin{aligned} IR_{net} &= k_c E_{pot} - P_{eff} && \text{if } k_c E_{pot} > P_{eff} \\ IR_{net} &= 0 && \text{otherwise} \end{aligned} \tag{1}$$

with IR_{net} = net irrigation requirement per unit area [mm/d]; P_{eff} = effective precipitation [mm/d]; E_{pot} = potential evapotranspiration [mm/d]; k_c = crop coefficient [dimensionless].

Crop coefficient k_c is a function of the crop type (rice and non-rice) and the day of the growing season. P_{eff} is the fraction of the total precipitation P that is available to the crop and does not run off. Without detailed site-specific information, P_{eff} is very difficult to determine. We use a simple approximation following the USDA Soil Conservation Method, as cited in Smith (1992, p. 21), with

$$\begin{aligned} P_{eff} &= P(4.17 - 0.2P)/4.17 && \text{for } P < 8.3 \text{ mm/d} \\ P_{eff} &= 4.17 + 0.1P && \text{for } P \geq 8.3 \text{ mm/d}\,. \end{aligned} \tag{2}$$

CROPWAT uses monthly precipitation data from which 10-day-averages are derived as input for the calculations (Smith, 1992). Application of Equation (1) with daily precipitation values, i.e., with days with and without precipitation, would lead to a gross overestimation of IR_{net}. In this case, the relatively high precipitation on the wet days in excess of the daily potential evapotranspiration would be lost, while a temporal averaging of the precipitation simulates the capacity of the soil to store the precipitation. Therefore, in GIM, the daily precipitation values are averaged over either 10 or 3 days. The averaging period of 3 days simulates the operation of paddy rice fields in Asia, where due to inundation and water-saturated soils only little precipitation can be stored, which leads to a higher IR_{net}.

2.5. MODEL VALIDATION

The accuracy of the model results can be assessed only in a rough manner, which is due to limited independent data available at the scale of the model. The simulated cropping patterns (in particular the rice growing areas) and growing seasons generally appear to reflect reality, but given the simplicity of the model, only the dominant features are represented and some discrepancies certainly occur (Döll and Siebert, 2001). The evaluation of the quality of the computed irrigation requirements is hampered by the high uncertainty of most published information; irrigation water use is generally not measured or even registered. Besides, even the value of the total irrigated area within a country is, for most countries, rather uncertain (Döll and Siebert, 2000). Comparisons of simulated irrigation requirements to independent data on irrigation water use in countries with apparently reliable information indicate that the irrigation model tends to somewhat overestimate the actual water use. This might be consistent with the model approach of computing optimal water requirements, and not actual (suboptimal) water uses. Independent data are, in general, only available for withdrawal water use (gross irrigation requirements) such that an additional source of uncertainty, the assumed irrigation water use efficiency, affects the comparison to independent data. In the case of Israel, the model would underestimate IR_{net} by 50% if we assumed an irrigation water use efficiency of 0.6, but by only 15% with an efficiency of 0.8 (Döll and Siebert, 2001). Egypt's irrigation requirement is underestimated by 28%, while China's is overestimated by 13% (Döll and Siebert, 2001).

Only for the U.S.A., there exists detailed information on irrigated areas as well as on consumptive and withdrawal water use for irrigation (for each county). There, the computed IR_{net} of 112 km^3/yr (1961–1990 climate normal) fits amazingly well to the observed consumptive use value of 113 km^3/yr (Solley et al., 1998). In order to check whether this correspondence is due to a canceling of errors, state averages of IR_{net} are compared, too. Also on the state level, the simulation results fit the independent data well, at least for states with a high net irrigation requirement (model efficiency of 0.975, 48 states, Döll and Siebert, 2001). The good correspondence in the case of the U.S.A., with the best information on irrigation water use worldwide, is encouraging. In conclusion, we think that the presented irrigation model is accurate enough for continental-scale or global-scale modeling.

3. Climatic Input: Defining Climate Change and Climate Variability

In order to assess the impact of climate change and climate variability on irrigation requirements, the irrigation requirements under the following climatic conditions are computed:

- present-day long-term average climatic conditions, i.e., the climate normal 1961–1990 ('baseline climate'),
- future long-term average climatic conditions of the 2020s and 2070s ('climate change'),
- 1-in-10 dry and wet years under climate conditions of 1901 to 1995 ('interannual climate variability'),
- long-term average climatic conditions, climate normals 1901–1930 and 1931–1960 ('long-term multidecadal climate variability').

The global irrigation model requires information on precipitation, temperature and potential evapotranspiration for each 0.5° grid cell. Potential evapotranspiration E_{pot} is computed according to Priestley and Taylor (1972) as a function of net radiation and temperature; net radiation is calculated following Shuttleworth (1993) based on the day of the year, latitude, sunshine hours and short-wave albedo. The albedo of irrigated land is here assumed to be 0.23. We follow the recommendation of Shuttleworth (1993) to set the Priestley–Taylor coefficient α to 1.26 for areas with relative humidity of approx. 60% or more and to 1.74 for other areas. Shuttleworth states that the resulting potential evapotranspiration is acceptable to an accuracy of 15% for estimating the evapotranspiration of the reference crop (short grass).

The climatic input of the global irrigation model is based on long time series of observed monthly values of precipitation, temperature, sunshine hours and number of wet days. These climate data that were collected and interpolated onto a grid of 0.5° by 0.5° by New et al. (2000). While for sunshine only the long-term average values of the period 1961–1990 are provided, the complete time series between 1901 and 1995 is available for precipitation, temperature and number of wet days. We corrected the precipitation values for measurement errors using the monthly 0.5° by 0.5° correction factors of Legates and Willmott (1990) based on a model for estimating the bias in precipitation gauge measurements caused by wind, wetting and evaporation losses.

Daily values of temperature and sunshine are calculated from the monthly values using cubic splines. Synthetic daily precipitation values are generated from the corrected monthly values by using the information on the number of wet days per month, such that there are days with and without precipitation. Following the approach of Geng et al. (1986), the sequence of wet and dry days in each month is simulated; then, the total monthly precipitation is distributed equally over all wet days of the month.

Long-term average IR_{net} under present climatic conditions is computed for the climate normal 1961–1990 (baseline climate). Cropping patterns and growing seasons are computed based on 30-year climatic averages, which reflects that in most cases, farmers cannot base their decision on when to start cropping on the unknown climate of the growing season that is about to begin. Long-term average irrigation requirements, however, are calculated by averaging 30-year time series of irrigation requirements. This averaging procedure leads to a more realistic estimate of the long-term average irrigation requirement than a calculation based on average climatic conditions. In the latter case, the irrigation requirement may be underestimated because it is not linear with respect to precipitation and potential evapotranspiration (comp. Equation (1)). In Japan, for example, with a low irrigation requirement per unit irrigated area, the error is 50%. On the global average, the underestimation would amount to only 2.4%.

3.1. CLIMATE CHANGE

In order to derive scenarios of future climate in the 2020s and the 2070s, the cell-values of observed monthly precipitation and temperature from New et al. (2000) were scaled by changes in precipitation and temperature calculated by two state-of-the-art GCMs: (1) the ECHAM4/OPYC3 model (Röckner et al., 1996; transient greenhouse gas and sulfate aerosol integration with forcing according to the IPCC IS92a scenario, see Leggett et al., 1992) and (2) the HadCM3 model (Gordon et al., 1999; transient all-anthropogenic forcing integration HC3AA with forcing similar to IS92a). In both cases, the decadal averages of mean monthly values of precipitation and temperature of the years 2020–2029 and 2070–2079 as well as, for present climate, the 1950–1979 (ECHAM4) and 1960–1989 (HadCM3) averages were used for scaling the observed values. Applying a simple interpolation procedure, the GCM results were interpolated from their original resolutions to the GIM resolution of 0.5 by 0.5°. Future changes in sunshine hours were not taken into account.

In order to compute long-term average IR_{net} under the climatic conditions of the 2020s and the 2070s, the monthly temperature and precipitation values of the each year of the climate normal 1961–1990 are scaled by the climate change as computed by the GCMs. In the case of temperature, the observed values are scaled by adding to them the difference of the GCM values of future and present-day temperature, while the 30-year perturbed precipitation time series was produced by multiplying the observed values with the future GCM precipitation as a ratio of the present-day GCM precipitation. This methodology implies that possible effects of climate change on climate variability are not taken into account; until now, GCMs cannot model well observed climate variability, and therefore they do not reliably simulate future climate variability.

3.2. CLIMATE VARIABILITY

IR_{net} in the typical dry and wet years is determined by first calculating the annual IR_{net}-values under the climatic conditions in each year between 1901 and 1995. For determining the cell-specific 1-in-10-dry-year irrigation requirement, the 9th highest IR_{net}-value that is computed for this time series is selected. This value will only be exceeded in 1 out of 10 years. For the 1-in-10-wet-year irrigation requirement, the 9th lowest IR_{net}-value is picked. Long-term average IR_{net} for the climate normals 1901–1930 and 1931–1960 is computed like IR_{net} for the baseline climate 1961–1990.

4. Results

Climate change has a two-fold effect on long-term average irrigation requirements per unit irrigated area. On the one hand, the optimal cropping patterns and growing seasons differ from those under baseline climatic conditions, and, on the other hand, the irrigation requirement of a certain crop on a given day of the year changes. The impact of interannual climate variability on irrigation requirements is modeled to be due to the latter effect only. The results obtained with the ECHAM4 climate change scenarios are presented first, followed by a comparison to the impacts computed with the HadCM3 climate change scenario; this sequence does not imply any value judgement on the quality of two GCMs.

4.1. IMPACT OF CLIMATE CHANGE ON CROPPING PATTERNS AND GROWING SEASONS

The cropping patterns and growing seasons of an irrigated area are strongly influenced by temperature and precipitation conditions. In GIM, temperature determines whether rice can be grown and which areas within a world region are best suited for multicropping, and the growing seasons are identified based on optimal temperature and precipitation conditions. For selected cells around the globe, Table I shows how cropping patterns and the starting dates of the growing seasons could change by the 2020s due to climate change as computed by ECHAM4. The cropping pattern changes in only one out of the ten cells: in the cell in the southeast of the U.S.A., rice is replaced by non-rice, which is due to higher temperatures and thus improved rice growing conditions elsewhere in the U.S.A. The growing seasons shift in all but two cells, often by approximately one month. Looking at larger-scale patterns, there are climate-dependent shifts of the areas with multicropping in Egypt and South Asia. In Egypt, for example, modeling of the cropping pattern results, for the baseline climate, in two crops per year in the southern part and only one crop per year in the central part, and vice versa for the 2020s. In the northern part of Egypt, multicropping is modeled to occur both today and in the future. The starting dates of the growing seasons are simulated to shift by at least a week in most of the irrigated cells world-wide. Particularly in the subtropical zones, the growing season, i.e., the season of the year with the optimal climate conditions for crop growth, is typically shifted into the (warmer) winter season.

4.2. IMPACT OF CLIMATE CHANGE ON NET IRRIGATION REQUIREMENTS

Optimal cropping patterns or growing seasons under the climate conditions of the 2020s differ from those under baseline climate, and these changes alone lead to different values of the annual IR_{net}. The example of the cell in SE-England (Table I) shows that even if cropping pattern and growing season remain the same, IR_{net} may change significantly due to climate change.

Figure 1a provides a global map of IR_{net} per unit irrigated area for the baseline climate. Only cells with a significant total irrigation requirement are shown, i.e., cells with irrigated areas in 1995 in which IR_{net} averaged over the total cell area was higher than 1 mm/yr. Clearly, the current climatic conditions are reflected,

Table I

Impact of climate change on cropping patterns, growing seasons and net irrigation requirements IR_{net} per unit irrigated area in selected cells

Grid cell	First day of growing season(s) [a]		IR_{net}, mm/yr	
	Baseline	2020s	Baseline	2020s
SE-England 52.75° N, 0.75° E	nr: May 19	nr: May 19	77	129
N-Germany 52.75° N, 10.25° E	nr: May 19	nr: May 31	72	99
NE-China 42.75° N, 125.75° E	nr: May 23	nr: May 23	16	16
W-Spain 39.25° N, 5.75° W	nr: April 11	nr: March 8	771	701
N-Egypt 31.25° N, 30.75° E	r/nr: April 1/Aug. 29 nr/nr: Jan. 15/June 14	r/nr: March 30/Aug. 27 nr/nr: Feb. 15/July 15	1393	1460
S-China 28.75° N, 115.75° E	r/nr: April 7/Sept. 4	r/nr: March 24/Aug. 21	234	238
SE-U.S.A. 27.25° N, 81.25° W	r: May 27	nr: June 20	87	54
NE-Brazil 4.75° S, 37.75° W	r/r: Jan. 28/July 6 nr: Jan. 18	r/r: Jan. 28/July 6 nr: Jan. 31	252	298
Chile 28.75° S, 70.75° W	nr: Nov. 8	nr: Oct. 26	725	771
S-Australia 37.75° S, 144.75° E	nr: Sept. 21	nr: Aug. 23	652	587

[a] nr: non-rice, r: rice, r/nr: rice in the first growing season, non-rice in the second.
Irrigated areas of 1995, under 1961–1990 average observed climate ('baseline'), and scaled with ECHAM4/OPYC3 climate scenario for 2020–2029 ('2020s').

with IR_{net} being highest in hot and arid regions such as Northern Africa and lowest in cold or humid regions such as Northern Europe and Southeast Asia. Figure 1b presents the percent changes of IR_{net} by the 2020s as computed with the ECHAM4 climate scenario. In order to interpret these changes, it is helpful to look at the changes in the climate variables. While annual average temperature will increase in all regions with irrigation, the precipitation change patterns are much more complex. Figure 2 (top) indicates the changes of annual precipitation that ECHAM4 computes for the 2020s. Note, however, that it is not the annual precipitation values that affect IR_{net} but the monthly ones, as they determine the start of the growing season and the situation during the growing season. Therefore, even in regions where annual precipitation decreases, IR_{net} may decrease, too, due to the following reasons: (1) more precipitation during the growing period, (2) a shift in the modeled growing period due to the change in temperature and precipitation in the cell (e.g., towards the winter when temperatures rise above optimal temperatures in the summer, see Section 2.3), (3) a change in the modeled cropping pattern due to the change in temperature and precipitation within the world region.

Until the 2020s, irrigation requirements increase in most irrigated areas north of 40° N, by up to 30% (Figure 1b), which is mainly due to decreased precipitation, in particular during the summer. South of this latitude, the pattern becomes complex. For most of the irrigated areas of the arid northern part of Africa and the Middle East, IR_{net} decreases. In Egypt, a decrease of about 50% in the southern part is accompanied by an increase of about 50% in the central part. These changes are mainly due to the climate-dependent shift of the areas in which multicropping is done (see Section 4.1). Similarly, in India cells with a strong increase border cells with a strong decrease, which is also due to changing cropping pattern. In central India, baseline IR_{net}-values of 250–350 mm are computed to more than double by the 2020s. In large parts of China, the impact of climate change is negligible (less than 5%), with decreases in northern China, as precipitation is assumed to increase (Figure 2). In general, climate change impacts are simulated to increase in magnitude by the 2070s (not shown).

When the cell-specific net irrigation requirements (in km^3/yr) are summed up over the world regions, increases and decreases of the cell values caused by climate change average out, at least to a large degree (Table II). The irrigation requirement increases in 11 out of the 17 world regions by the 2020s, but not more than 10% (except Southeast Asia with 19%). By the 2070s, an increase will have occurred in 12 regions, 10 of which also showed an increase by the 2020s. The highest absolute increases are predicted for South Asia (Pakistan, India and Bangladesh), and the highest relative increases for Southeast Asia where per hectare IR_{net} is low. IR_{net} in Northern Africa and the Middle East is computed to decrease by about 5% until the 2020s and by about 15% until the 2070 even though temperatures increase and precipitation decreases in the major irrigated regions (e.g., the Nile and the Euphrates/Tigris basins, see Figure 2 and Table III). This is explained by the climate-induced shift of the (optimal) growing seasons to the winter months when solar radiation and thus potential evapotranspiration is lower; global warming causes the summer temperatures to exceed the optimal temperatures for crop growth. The global net irrigation requirement is computed to increase by 3.3% in the 2020s and by 5.5% in the 2070s, from 1092 km^3/yr for the baseline climate. According to our computations, IR_{net} will increase on 66% of the irrigated area of 1995 until the 2020s, and on 62% until the 2070s. Thus climate change, with a global increase in temperature and precipitation, might result in a global increase

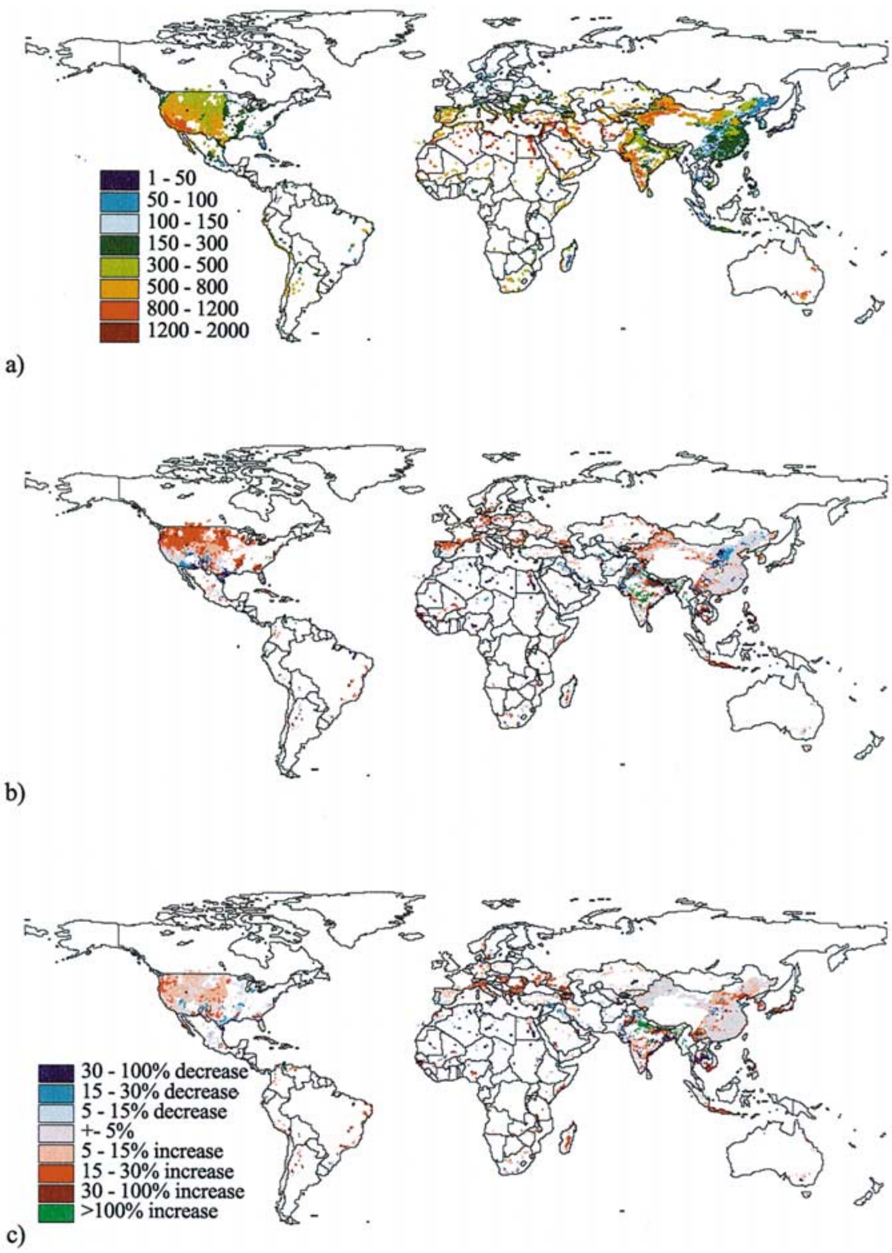

Figure 1. (a) Net irrigation requirement IR_{net} per unit irrigated area under baseline climate (1961–1990) [mm/yr]. (b) Change of IR_{net} between baseline climatic condition and the 2020s, due to climate change as computed by ECHAM4. (c) Like (b), but due to climate change as computed by HadCM3. Only those cells are shown in which IR_{net} per unit cell area was more than 1 mm/yr (baseline climate, 1995 irrigated areas).

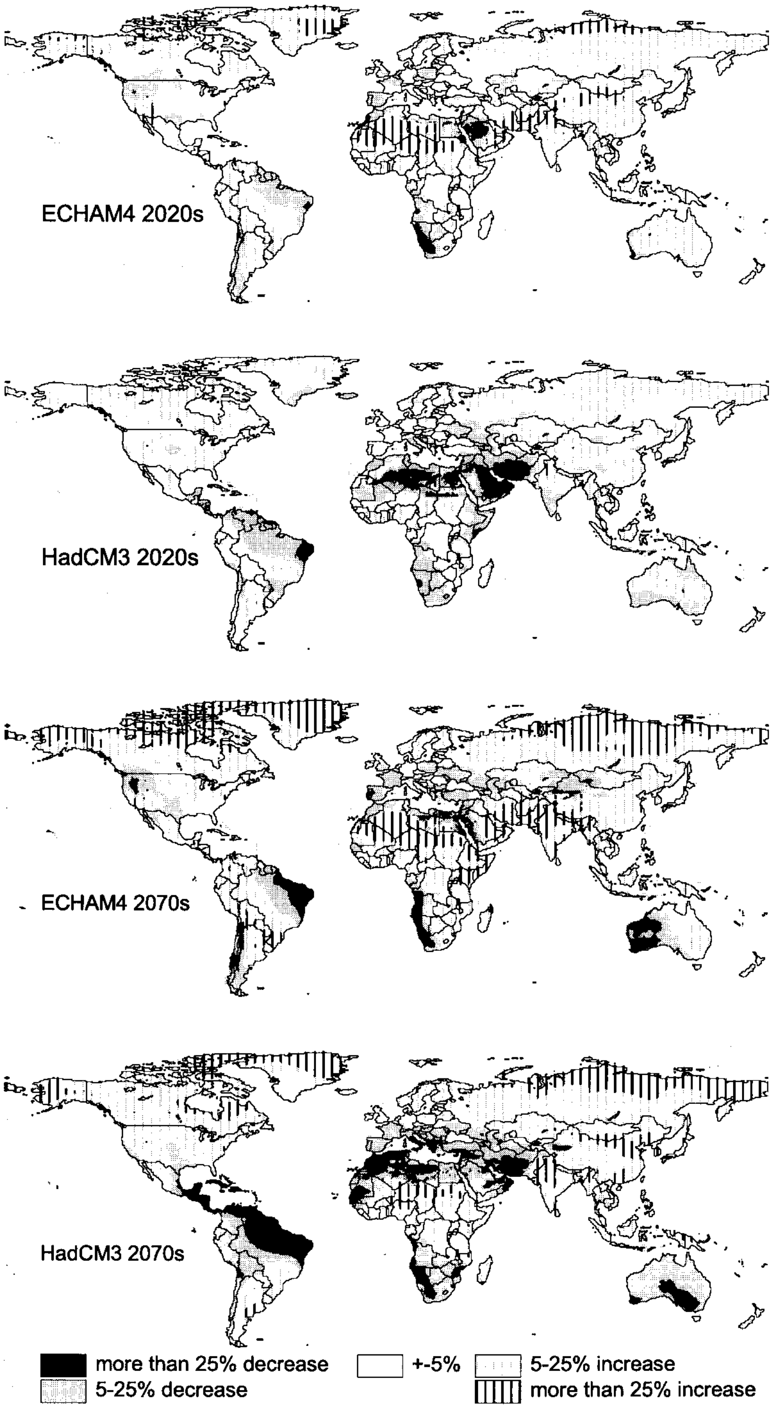

Figure 2. Change of annual precipitation between baseline climatic condition and the 2020s/2070s, as computed by ECHAM4 and HadCM3.

Table II

Impact of climate change on computed net irrigation requirements IR_{net} of world regions

	Irrigated area 1995, 1000 km^2	Cropping intensity	Long-term average IR_{net}, km^3/yr				
			Baseline	2020s		2070s	
				ECHAM4	HadCM3	ECHAM4	HadCM3
Canada	7.1	1.0	2.4	2.9	2.7	3.3	2.9
U.S.A.	235.6	1.0	112.0	120.6	117.9	123.0	117.9
Central America	80.2	1.0	17.5	17.0	17.6	18.1	19.7
South America	98.3	1.0	26.6	27.1	27.5	28.2	29.1
Northern Africa	59.4	1.5	66.4	62.7	65.3	56.0	57.7
Western Africa	8.3	1.0	2.5	2.2	2.4	2.4	2.6
Eastern Africa	35.8	1.0	12.3	13.1	12.2	14.5	14.3
Southern Africa	18.6	1.0	7.1	7.0	7.4	6.4	7.2
OECD Europe	118.0	1.0	52.4	55.8	55.2	56.5	57.8
Eastern Europe	49.4	1.0	16.7	18.4	19.0	19.7	22.1
Former U.S.S.R.	218.7	0.8	104.6	106.6	112.1	104.4	108.7
Middle East	185.3	1.0	144.7	138.7	142.4	126.5	137.8
South Asia	734.6	1.3	366.4	389.8	400.4	410.7	422.0
East Asia	492.5	1.5	123.8	126.0	126.6	131.3	127.1
Southeast Asia	154.4	1.2	17.1	20.3	18.8	30.4	28.6
Oceania	26.1	1.5	17.7	17.8	17.6	18.2	19.7
Japan	27.0	1.5	1.3	1.3	1.8	1.4	1.5
World	**2549.1**		**1091.5**	**1127.5**	**1147.0**	**1151.0**	**1176.8**

Irrigated areas of 1995, under 1961–1990 average observed climate ('baseline'), and scaled with ECHAM4/OPYC3 or HadCM3 climate change scenarios for 2020–2029 ('2020s') and 2070–2079 ('2070s').

of IR_{net} and, concurrently, an increase of IR_{net} on two thirds of the area equipped for irrigation in 1995.

In order to assess the problem of water scarcity, and for water management decisions, the appropriate averaging units for irrigation requirements are not world regions or countries but river basins. Table III lists a few large river basins with extensive irrigation and their total long-term average irrigation requirements for baseline and changed climatic conditions. Even today, the water quantity situation in all the basins can be regarded as stressed. Climate change has almost no effect on total IR_{net} in three of the nine basins (Colorado, Huangho/Tientsin and Murray/Darling). It leads to a decrease of IR_{net} in two (Nile, Euphrates/Tigris) and to an increase in four basins (Indus, Ganges, Godavari, Mississippi). The high increase in the Godavari basin, by more than 50%, is mainly due to the shift of areas with multicropping within South Asia to the basin. In the Mississippi basin, where no multicropping is assumed to occur, IR_{net} increases by 15%, or 6 km^3/yr, in the 2020s and by 13% in the 2070s.

4.3. IMPACT OF CLIMATE VARIABILITY ON NET IRRIGATION REQUIREMENTS

For an assessment of water scarcity, it is necessary to consider not only the situation under long-term average climatic conditions but also in typical dry years. Regions with a high interannual climate variability suffer more from water scarcity than comparable regions with a more even climate. Figure 3a shows how much IR_{net} in a 1-in-10 dry year is increased compared to the baseline climate. Only in 1 out of 10 years will IR_{net} even be higher. The 1-in-10 dry year is cell-specific, i.e., that the high demands do not occur simultaneously in a river basin. The increase of IR_{net} in the 1-in-10 dry year is a measure of the climate variability to which the farmer and the irrigation water supply has to respond. In such years, the water supply must be increased by the amount shown in Figure 3a, as compared to average climatic conditions, or the farmer cannot irrigate the total irrigated area with the optimal amount of water. In general, the higher the long-term average IR_{net} is, the lower the percentage increase in the cell-specific 1-in-10 dry year will be. However, there are regional differences; for the same average values, the variability is higher in North America and Southern Africa than in Europe and Northern Africa. In regions with a high average IR_{net} (above 800 mm/yr), where essentially all the water necessary for crop growth must be provided by irrigation, the increase of IR_{net} in a 1-in-10 dry year is low (e.g., in Northern Africa less than 10% or 20–70 mm/yr). In regions with an average IR_{net} of 300–800 mm/yr, the increase is more significant (e.g., in Southeast Europe 10–30% or 60–100 mm/yr, and in the western U.S.A. 10–50% or 80–240 mm/yr). Where the average IR_{net} is between 150 and 300 mm/yr, increases of 30–50% may occur, such as in southeastern China (corresponding to 50–150 mm/yr) or even of 50–100%, such as in the eastern U.S.A. (corresponding to 70–200 mm/yr). It is rather seldom that IR_{net} in a cell-specific 1-in-10 dry year is more than double the value under average climatic conditions. This occurs in regions

Table III
Impact of climate change on computed net irrigation requirements IR_{net} of large river basins

	Irrigated area 1995, 1000 km^2	Long-term average IR_{net}, km^3/yr				
		Baseline	2020s		2070s	
			ECHAM4	HadCM3	ECHAM4	HadCM3
Murray/Darling (Australia)	16.2	12.6	12.4	12.1	12.9	14.0
Huangho/Tientsin Basin (China)	94.3	31.4	31.1	32.7	35.7	32.0
Indus (Pakistan)	146.5	85.6	88.2	92.4	77.8	96.2
Ganges	189.3	61.5	63.4	93.5	74.6	66.4
Godavari (India)	33.5	13.5	20.9	13.9	24.2	23.0
Euphrates/Tigris	65.2	53.4	50.1	48.1	40.3	45.5
Nile	49.8	47.0	47.0	46.6	41.5	41.5
Mississippi (U.S.A.)	105.4	39.2	45.2	42.0	44.1	44.4
Colorado (U.S.A./Mexico)	12.5	7.7	7.2	7.8	7.5	7.4

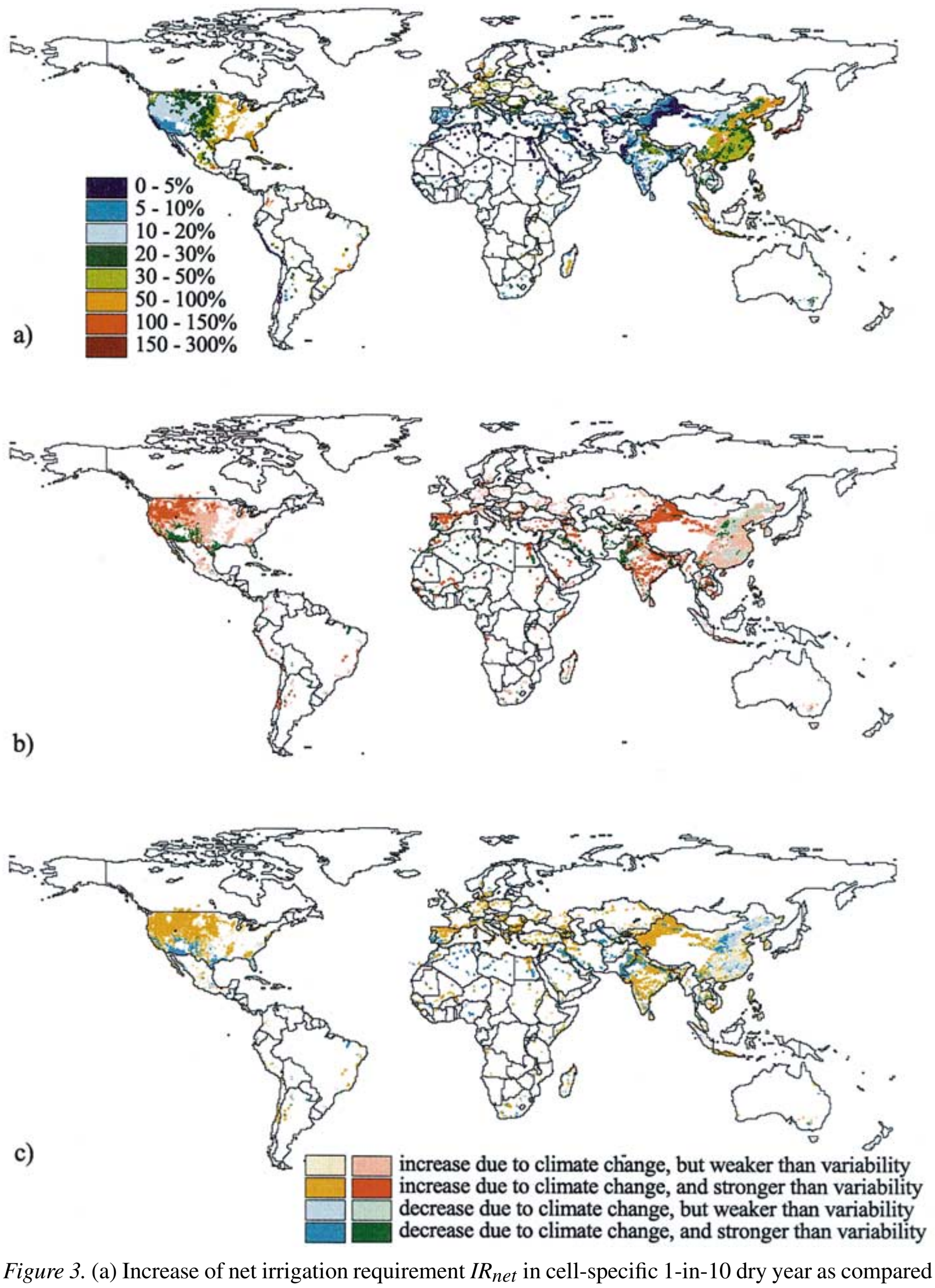

Figure 3. (a) Increase of net irrigation requirement IR_{net} in cell-specific 1-in-10 dry year as compared to IR_{net} under baseline climate (irrigated areas of 1995). (b) and (c) Impact of climate change according to ECHAM4 vs. impact of climate variability on IR_{net}. (b) Change of IR_{net} between baseline climatic condition and the 2020s compared to the difference of IR_{net} under baseline climate and in the 1-in-10 dry (or wet) year (interannual variability). (c) Change of IR_{net} between baseline climatic condition and the 2020s as compared to the maximum difference of IR_{net} for the three climate normals 1901–1930, 1931–1960 and 1961–1990 (multidecadal variability). Only those cells are shown in which IR_{net} per unit cell area was more than 1 mm/yr (baseline climate, 1995 irrigated areas).

with rather small requirements per unit irrigated area (average IR_{net} 40–60 mm/yr) such as in Japan, northeastern China and Mexico.

4.4. COMPARISON OF THE IMPACT OF CLIMATE CHANGE TO THE IMPACT OF CLIMATE VARIABILITY

To compare the impact of climate change on irrigation requirements to the impact of climate variability such that the severity of climate change impacts can be assessed, a precise definition of both terms is necessary. The impact of climate change on IR_{net} in decade X is expressed as the difference to the average IR_{net} for the climate normal 1961–1990:

$$IR_{net\_avg}(X) - IR_{net\_avg}\,(1961\text{–}90)\,. \tag{3}$$

There are a variety of measures of climate variability. Here, the impact of climate variability is defined by two measures, one expressing interannual variability and one expressing the long-term multidecadal variability. Interannual climate variability is expressed in terms of the 1-in-10 dry or 1-in-10 wet year as

$$\begin{aligned} &IR_{net\_1-in-10-dry-year}\,(1901\text{–}95) - IR_{net\_avg}\,(1961\text{–}90) \text{ if} \\ &\quad IR_{net\_avg}(X) \geq IR_{net\_avg}\,(1961\text{–}90) \\ &IR_{net\_avg}\,(1961\text{–}90) - IR_{net\_1-in-10-wet-year}\,(1901\text{–}95) \text{ if} \\ &\quad IR_{net\_avg}(X) < IR_{net\_avg}\,(1961\text{–}90)\,. \end{aligned} \tag{4}$$

If the cell-specific IR_{net} increases due to climate change, the climate change impact is compared to the impact of a 1-in-10 dry year, and if IR_{net} decreases due to climate change, climate variability is defined in term of a 1-in-10 wet year. The multidecadal climate variability measure reflects the long-term variability of irrigation requirements (per unit irrigated area) during the 20th century and is defined in terms of the three climate normals of the 20th century as

$$\max \begin{pmatrix} |IR_{net\_avg}\,(1961\text{–}90) - IR_{net\_avg}\,(1931\text{–}60)|\,, \\ |IR_{net\_avg}\,(1961\text{–}90) - IR_{net\_avg}\,(1901\text{–}30)|\,, \\ |IR_{net\_avg}\,(1931\text{–}60) - IR_{net\_avg}\,(1901\text{–}30)|\,, \end{pmatrix}. \tag{5}$$

Figures 3b,c compare the impact of climate change by the 2020s as computed by ECHAM4 with the impact of interannual and multidecadal climate variability, respectively. In most of Europe, China and Australia and in the Midwest of the U.S.A., the impact of climate change on IR_{net} is smaller than that of interannual climate variability as defined by the 1-in-10 year (Figure 3b). The opposite is true e.g. for the western U.S.A., for Spain, Egypt and most of India. The differences between the IR_{net}-values for the three 30-year climate normals of the 20th century are smaller than the differences between the IR_{net}-values for the baseline climate and the IR_{net}-values in the 1-in-10 year; in Figure 3c, climate change impacts are

Table IV
Impact of climate change vs. impact of climate variability on net irrigation requirement

	Percent of global irrigated area			
	Variability: 1-in-10 dry/wet year		Variability: multidecadal	
	2020s	2070s	2020s	2070s
Increase of IR_{net} due to climate change but weaker than impact of climate variability	46 *50*	28 *25*	24 *27*	13 *11*
Increase of IR_{net} due to climate change and stronger than impact of climate variability	20 *19*	34 *39*	42 *42*	49 *53*
Decrease of IR_{net} due to climate change but weaker than impact of climate variability	16 *18*	13 *14*	9 *12*	8 *8*
Decrease of IR_{net} due to climate change and stronger than impact of climate variability	18 *13*	25 *22*	25 *19*	30 *26*
	100 *100*	100 *100*	100 *100*	100 *100*

Irrigated areas of 1995, ECHAM4 (top) and HadCM3 (bottom, in italics) climate change scenarios.

seen to dominate most irrigated areas of the globe (except in China). This shows that the expected anthropogenic climate change in the first decades of the 21st century will have a larger impact on irrigation requirements almost worldwide than the long-term climate variations that occurred during the 20th century.

Table IV indicates the percentages of the global irrigated area for which the impact of climate change is stronger or weaker than the impact of climate variability. Considering the interannual variability of the 1-in-10 year, in the 2020s climate change dominates over climate variability on 38% of the areas equipped for irrigation in 1995, and on 59% in the 2070s. On 20% of the area, in the 2020s, and on 34%, in the 2070s, IR_{net} will have increased compared to the baseline climate, and the increase will be larger than the differences between IR_{net} in the 1-in-10 dry year and under baseline climate. Looking at the long-term climate variability of the 20th century, this critical area increases to 42% (2020s) and 49% (2070s) of the total irrigated area.

4.5. INFLUENCE OF THE SELECTED CLIMATE MODEL

Ideally, the ECHAM4 and the HadCM3 climate change scenarios should be similar as they are computed based on very similar scenarios of anthropogenic emissions. However, the calculated values of future precipitation and temperature differ significantly; the reasons for this are concisely discussed in Arnell (1999). On the global average, ECHAM4 predicts a warmer but much wetter climate than HadCM3 for the 2020s, and an even wetter climate for the 2070s with smaller temperature changes than HadCM3, in particular at low latitudes. In particular, the spatial patterns of precipitation changes of the two climate scenarios differ considerably (Figure 2). Both, however, predict, for the 2020s, strongly decreased precipitation in Egypt and the Arabian Peninsula, Northeast Brazil and the eastern part of Southern Africa. In North America and most of Europe, the precipitation decrease is less pronounced in the HadCM3 scenario than in the ECHAM4 scenario, while the opposite is true for Italy, Southeast Europe and southern parts of the former Soviet Union. In northern China, the ECHAM4 model results in a strong precipitation increase while the HadCM3 model computes, in some areas, a precipitation decrease. These differences in precipitation changes are reflected by the respective computed changes of IR_{net} shown in Figures 1b (ECHAM4) and 1c (HadCM3).

Under the HadCM3 scenario for the 2020s, IR_{net}-values of 11 out of the 17 world regions are higher than those under the ECHAM4 scenario (Table II). The global IR_{net} increases are approximately 50% larger under the HadCM3 scenario as compared to the ECHAM4 scenario (increases of 5.1% vs. 3.3% until the 2020 and 5.5% vs. 7.8% until the 2070s). Looking at the river basins (Table III), both climate scenarios agree well for the Nile. For the Euphrates/Tigris basin, both scenarios result in a decrease of IR_{net}, but show different dynamics. The differences in the Indus basin can be explained mainly by different precipitation scenarios. The very different estimates for the Godavari and Ganges basins result from both different estimates of precipitation change and multicropping (the latter due to different estimates of temperature change).

When comparing the impact of climate change to the impact of climate variability, the spatial pattern resulting from the two different climate scenarios correspond to those in Figures 1b,c. For the global totals, the differences between the results for the two GCMs are small (Table IV). Under both climate scenarios, the area dominated by climate increases from the 2020s to the 2070s.

5. Discussion and Conclusions

This global-scale study examines and quantifies the impacts of climate change and climate variability on net irrigation requirements IR_{net} and thus provides new information required for addressing the issues of water and food scarcity in the

21st century. Applying the Global Irrigation Model GIM, it combines the best information currently available on the global scale into a first model-based analysis. For areas that were equipped for irrigation in 1995, GIM does not only simulate the effect of climate change on IR_{net} during the present-day growing seasons, but also the climate-induced change in cropping patterns and growing seasons. The severity of the climate change impact on IR_{net} is assessed by comparing the impact of climate change to the impact of climate variability.

To evaluate the significance of the results of this study, it is necessary to discuss the many sources of uncertainty. First of all, (almost) the same scenarios of greenhouse gas emissions result in rather different climate change scenarios, if simulated by different GCMs (see Figure 2). Thus, irrigation modeling can only aim at providing the best estimate of the impact of GCM-specific climate scenarios on irrigation requirements, and not at a direct estimate of the impact of certain anthropogenic greenhouse gas emissions.

Another type of uncertainty is related to the way how GCM results are applied in the study. Due to the low spatial resolution of GCMs and their inability to reproduce current climate appropriately, it is necessary to create 'secondary' climate scenarios by combining the best estimate of historic climate with climate change as simulated by GCMs (see Section 3.1). This leads to climate patterns that are no longer 'physical' in the sense that they do not obey the rules of conservation of mass, momentum and energy, and in particular if the values of the observed and modeled current climate variables differ significantly, the resulting secondary climate scenario might not be plausible anymore. In this study, the secondary climate scenario did not take into account changes in humidity and sunshine hours (cloudiness), which, at least globally averaged, should lead to an overestimation of future potential evapotranspiration and thus IR_{net}. However, it is well known that the modeling of clouds and water vapor in the atmosphere is one of the main sources of uncertainty in climate modeling (IPCC, 2001). Besides, the fact that GCMs generally do not consider the effects of increase CO_2 concentrations on plant physiology, possibly leads to an underestimation of regional warming and an overestimation of humidity (and cloudiness) in particular over tropical continents (IPCC, 2001). Due to these uncertainties in climate modeling, it currently does not appear to be advisable to include changes in humidity and cloudiness in studies on the impact of climate change on irrigation requirements. Unfortunately, it is not possible to say what the consequences of this non-inclusion are for the modeled changes of IR_{net}.

The lack of knowledge on presently irrigated crops (what crop is irrigated where and when), which results in the simplistic modeling of the cropping pattern and the growing seasons of only two crops (rice and non-rice), causes a high degree of uncertainty in the assessment of the current irrigation requirements as well as in the assessment of climate change impacts. In particular if perennial crops like sugar cane or banana are irrigated, they would be affected by climate change quite differently than the model crops with a growing period of only 150 days.

Any simulated climate-induced changes of the cropping pattern and of the start of the growing season (which are modeled by GIM with the aim of optimizing crop productivity and water requirements) can only indicate potential adaptation necessities. For example, if an area is simulated to switch to multicropping, this indicates that this area is more favored by climate change than other irrigated areas within the same world region. If the growing season is shifted towards the cooler part of the year, for example, this could indicate that for some crop types, temperature increase is detrimental to crop productivity in the summer. The changes in irrigation requirement that are due to the indirect impact of climate change (via cropping patterns and growing seasons), which occur, for example, in India, must be interpreted with care. However, for determining the impact of climate change on irrigation requirements, it appears to be appropriate to include these indirect climate change effects, as they represent, in a very coarse manner, the adaptation that would occur if farmers continued to select cropping patterns and growing seasons according to the same criteria for optimal climatic conditions as today. Obviously, any adaptation would be strongly affected by economic conditions, which are not considered in this study.

Finally, what are the possible implications of neglecting the impact of increased atmospheric CO_2 concentrations on crop physiology? If crop productivity remained the same, potential evapotranspiration and thus IR_{net} would decrease if CO_2 concentrations increased. 'More crop per drop', however, could also result in an increased crop productivity; then, the difference between the area-specific IR_{net} with and without consideration of the fertilization effect might become zero.

Currently, it is not possible to quantify the discussed uncertainties. Anyway, the actual impacts of climate change are much more complex than could be modeled here. A changing climate might, for example, worsen growing conditions or water availability in certain regions of the world so much that irrigated agriculture must shift to other regions.

Thus, when interpreting the results of the study summarized below, its limits and the related uncertainties need to be kept in mind. The simulations of irrigation requirements under two climate change scenarios indicate that climate change may, in most areas, lead to a shift in the optimal growing period, often by a month or more into the winter season, and may sometimes even cause a change in the cropping pattern. Although anthropogenic climate change is expected to lead to an increase in precipitation over land globally, the simulation of climate change impacts on IR_{net} on the areas equipped for irrigation in 1995 indicates that IR_{net} is likely to increase on about two thirds of these areas by the 2020s (and the 2070s). This is due to the increased temperature and thus potential evapotranspiration, and to the strong spatial heterogeneity of precipitation increases and decreases. Increases (or decreases) of IR_{net} of up to 30% are common even without a change in the cropping intensity.

On about 20% (for the 2020s) and 35% (for the 2070s) of the irrigated area, the increase of IR_{net} resulting from climate change will be stronger than the increase of IR_{net} in a 1-in-10 dry year compared to average climatic conditions. On 42% and 50%, respectively, the anthropogenic climate change in the 21st century will lead to an increase of IR_{net} that is stronger than the impact of the long-term climate variations that occurred during the 20th century.

The global total of IR_{net} is computed to increase by 3–5% until the 2020s and by 5–8% until the 2070s. On the scale of world regions, the modeled increases are largest in South Asia, the region with the largest current IR_{net}, where up to 15% (or 56 km^3/yr) more water will be required in the 2070s for irrigating the same areas as today. The second most important world region with respect to irrigation, the Middle East, is simulated to experience a small decrease in IR_{net}, caused mainly by a shift of the growing seasons towards the winter. The third most important region, East Asia (mainly China), will not be affected much. However, it has to be stressed that averaging changes in IR_{net} over world regions or the globe is meaningful only for an assessment of food security under conditions of functioning regional or global markets.

For questions related to water resources management, river basins are the appropriate averaging unit. At the river basin scale, the differences between the climate scenarios computed by different GCMs are generally significant. Nevertheless, for the large river basins of the world with extensive irrigation, at least the tendencies (decrease or increase) of the changes of IR_{net} computed with the two climate scenarios are mostly the same. According to both GCMs, the Mississippi basin (where no multicropping is assumed to take place) will suffer from an increase of IR_{net} of about 15%. For the Ganges and Godavari, the large discrepancies between the increases of IR_{net} derived from the two climate scenarios stem from the climate-dependent reallocation of areas with multicropping among the river basins of South Asia, while for the Indus, the discrepancies are due to different precipitation patterns. The highly stressed river basins Colorado, Hoangho/Tientsin, Murray/Darling, Euphrates/Tigris and Nile, in which IR_{net} is of the same order of magnitude as the measured discharges, will not be affected much by climate change or even have decreasing requirements. In these basins, however, even small increases of IR_{net} will cause problems. Besides, it is important to note that in river basins with a future climate-induced increase of IR_{net}, the very likely concurrent decrease of the natural discharge will make it more difficult to fulfill the additional water demand.

What implications does this study have for the future of irrigated agriculture? It shows clearly that assessments of the possibilities of extending irrigation should consider the impact of climate change on irrigation requirements. The negative impact that climate change is likely to have in many regions of the globe, through increased per hectare irrigation requirements, may be yet another factor limiting irrigation. It is advisable to consider a shift of irrigated agriculture to regions where climate change will decrease per hectare irrigation requirements. In any case, however, comprehensive assessments are necessary, which take into account the future water use by the domestic and industrial sectors as well as the future water resources situation.

Acknowledgments

The author appreciates the constructive criticism of two anonymous reviewers, which substantially helped to improve the paper.

References

Adams, R. M., Rosenzweig, C., Peart, R. M., Ritchie, J. T., McCarl, B. A., Glyer, J. D., Curry, R. B., Jones, J. W., Boote, K. J., and Allen, L. H.: 1990, 'Global Climate Change and U.S. Agriculture', *Nature* **345**, 219–224.

Alcamo, J., Henrichs, T., and Rösch, T.: 2000, *World Water in 2025 – Global Modeling and Scenario Analysis for the World Commission on Water for the 21st Century*, Kassel World Water Series Report 2, Center for Environmental Systems Research, University of Kassel, Germany (can be downloaded from http://www.usf.uni-kassel.de/usf/archiv/dokumente.en.htm).

Allen, R. G., Gichuki, F. N., and Rosenzweig, C.: 1991, 'CO_2-Induced Climatic Changes in Irrigation-Water Requirements', *J. Water Resour. Plan. Manage.* **117**, 157–178.

Arnell, N. W.: 1999, 'The Effect of Climate Change on Hydrological Regimes in Europe: A Continental Perspective', *Global Environ. Change* **9**, 5–23.

Döll, P., Kaspar, F., and Alcamo, J.: 1999, 'Computation of Global Water Availability and Water Use at the Scale of Large Drainage Basins', *Mathematische Geologie* **4**, 111–118.

Döll, P. and Siebert, S.: 2000, 'A Digital Global Map of Irrigated Areas', *Int. Commission Irrigation Drainage J.* **49**, 55–66.

Döll, P. and Siebert, S.: 2001, 'Global Modeling of Irrigation Water Requirements', *Water Resour. Res.*, accepted.

FAO: 1995, *Digital Soil Map of the World and Derived Soil Properties*, CD-ROM Version 3.5, FAO, Rome.

Geng, S., Penning, F. W. T., and Supit, I.: 1986, 'A Simple Method for Generating Daily Rainfall Data', *Agric. For. Meteorol.* **36**, 363–376.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: 2000, 'The Simulation of SST, Sea Ice Extents and Ocean Heat Transports in a Version of the Hadley Centre Coupled Model without Flux Adjustments', *Clim. Dyn.* **16**, 147–168.

IPCC (Intergovernmental Panel on Climate Change): 2001, *Third Assessment Report*, Technical Summary of the Working Group I Report (can be downloaded from http://www.ipcc.ch/).

IRRI (International Rice Research Institute): 1988, *World Rice Statistics 1987*, IRRI, Manila (http://www.riceweb.org/).

Jones, R. N.: 2000, 'Exceeding the Risk of Climate Change Using an Irrigation Demand Model', *Clim. Res.* **14**, 89–100.

Legates, D. R. and Willmott, C. J.: 1990, 'Mean Seasonal and Spatial Variability in Gauge-Corrected, Global Precipitation', *Int. J. Clim.* **10**, 111–117.

Leggett, J., Pepper, W. J., and Swart, R. J.: 1992, 'Emission Scenarios for the IPCC: An Update', in IPCC, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.

McCabe, G. J. and Wolock, D. M.: 1992, 'Sensitivity of Irrigation Demand in a Humid-Temperate Region to Hypothetical Climatic Change', *Water Resour. Bull. Amer. Water Resour. Assoc.* **28**, 535–543.

New, M., Hulme, M., and Jones, P. D.: 2000, 'Representing Twentieth Century Space-Time Climate Variability. Part II: Development of 1901–96 Monthly Grids of Terrestrial Surface Climate', *J. Climate* **13**, 2217–2238.

Priestley, C. and Taylor, R.: 1972, 'On the Assessment of Surface Heat Flux and Evaporation Using Large Scale Parameters', *Mon. Wea. Rev.* **100**, 81–92.

Ramirez, J. A. and Finnerty, B.: 1996, 'CO_2 and Temperature Effects on Evapotranspiration and Irrigated Agriculture', *J. Irrigation Drainage Engineering – ASCE* **122**, 155–163.

Röckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dümenil, L., Esch, M., Giorgetta, M., Schlese, U., and Schulzweida, U.: 1996, *The Atmospheric General Circulation Model ECHAM-4: Model Description and Simulation of Present Day Climate*, MPI-Report No. 218, MPI für Meteorologie, Hamburg.

Seckler, D., Amarasinghe, U., Molden, D., de Silva, R., and Barker, R.: 1997, *Word Water Demand and Supply 1990 to 2025: Scenarios and Issues*, Research Report 19, International Water Management Institute, Colombo, Sri Lanka.

Shiklomanov, I. A. (ed.): 1997, 'Comprehensive Assessment of the Freshwater Resources of the World: Assessment of Water Resources and Water Availability in the World', World Meteorological Organization, Geneva, Switzerland.

Shuttleworth, W. J.: 1993, 'Evaporation', in Maidment, D. R. (ed.), *Handbook of Hydrology*, McGraw-Hill, pp. 4.1–4.53.

Smith, M.: 1992, *CROPWAT – A Computer Program for Irrigation Planning and Management*, FAO Irrigation and Drainage Paper 46, Rome.

Solley, W. B., Pierce, R. S., and Perlman, H. A.: 1998, *Estimated Use of Water in the United States in 1995*, USGS Circular 1200 (http://water.usgs.gov/watuse/pdf1995/html/).

Yates, D. N. and Strzepek, K. M.: 1996, 'Modeling Economy-Wide Climate Change Impacts on Egypt: A Case for an Integrated Approach', *Environ. Model. Assess.* **1**, 119–135.

(Received 22 January 2001; in revised form 15 November 2001)