Volume 60, Issues 3–4, February 2008
Completing volume 60

ISSN 0921-8181

GLOBAL and PLANETARY CHANGE

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Agricultural irrigation demand under present and future climate scenarios in China

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Abstract

The anticipated change of climatic conditions within the next decades is thought to have far reaching consequences for agricultural cropping systems. The success of crop production in China, the world's most populous country, will also have effects on the global food supply. More than 30% of the cropping area in China is irrigated producing the major part of the agricultural production. To model the effects of climate change on irrigation requirements for crop production in China a high-resolution (0.25°, monthly time series for temperature, precipitation and potential evapotranspiration) gridded climate data set that specifically allows for the effects of topography on climate was integrated with digital soil data in a GIS. Observed long-term trends of monthly means as well as trends of interannual variations were combined for climate scenarios for the year 2030 with average conditions as well as 'best case' and 'worst case' scenarios.

Regional cropping calendars with allowance for multiple cropping systems and the adaptation of the begin and length of the growing season to climatic variations were incorporated in the FAO water balance model to calculate irrigation amounts to obtain maximum yields for the period 1951–1990 and the climate scenarios.

During the period 1951–1990 irrigation demand displayed a considerable variation both in temporal and spatial respects. Future scenarios indicate a varied pattern of generally increasing irrigation demand and an enlargement of the subtropical cropping zone rather than a general northward drift of all zones as predicted by GCM models. The effects of interannual variability appear to have likely more impact on future cropping conditions than the anticipated poleward migration of cropping zones.
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Keywords: irrigation demand; climate change; water balance modeling; climate data; China

1. Introduction

The anticipated climatic changes will have considerable effects on cropping systems worldwide. Both positive and negative temperature and precipitation trends have been established with a fair degree of accuracy during recent decades (IPCC, 2001) while changes in global evaporation rates are still under discussion (Peterson et al., 1995; Brutsaert and Parlange, 1998; Ohmura and Wild, 2002; Roderick and Farquhar, 2002). The effects of climate on terrestrial ecosystems and particularly on agricultural food production however cannot be deduced directly from these observed climatic trends as plant response depends on the interaction of climatic, edaphic, topographic and anthropogenic factors.

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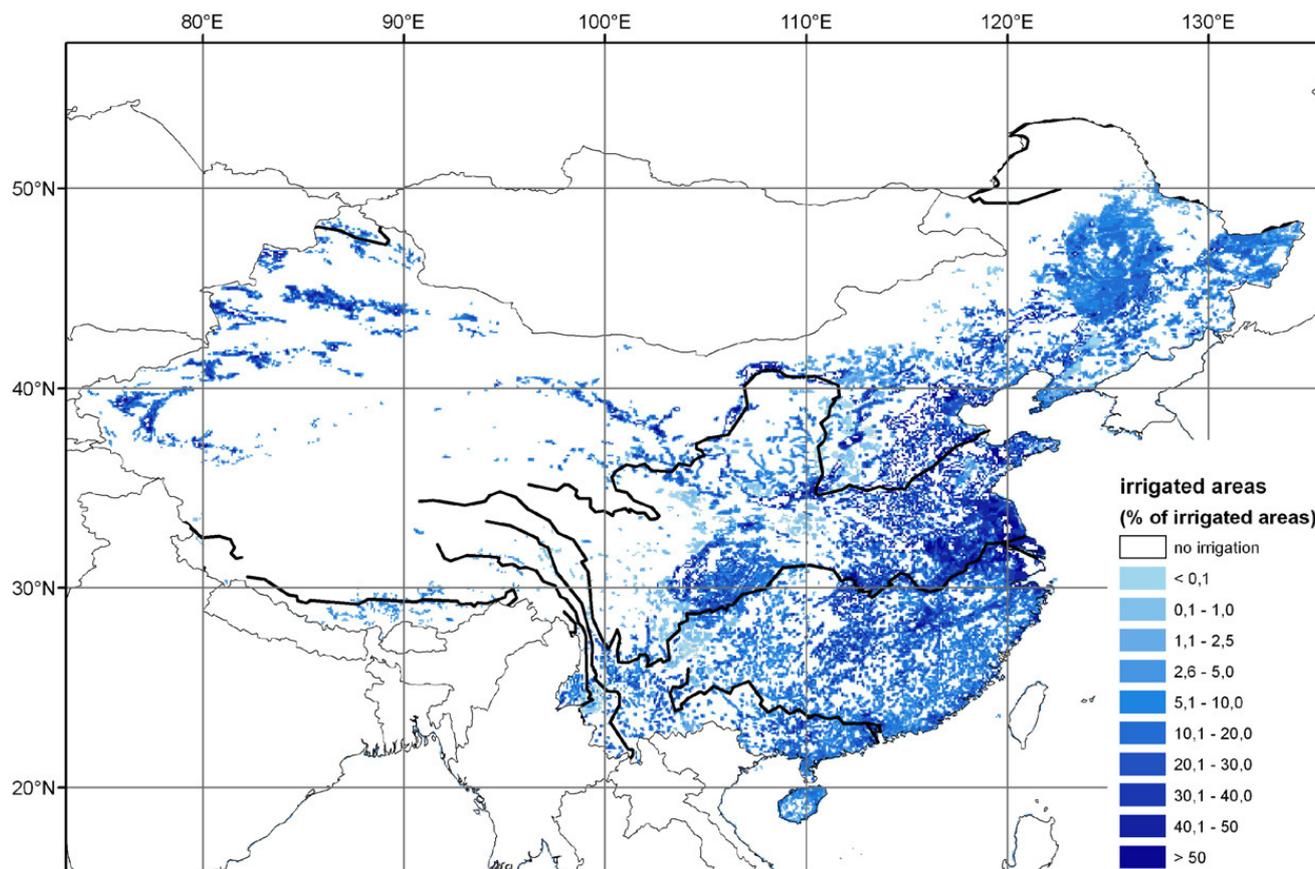
Fig. 1. Percentage of irrigated cropping areas in China. Source: Siebert et al. (2005).

Crop production in China, the country with the largest population of the world, has received considerable attention as any climate induced variations of the natural environment may have considerable impacts on the food production (Harris, 1996). For more than a decade water scarcity has been a major environmental and economic problem in China (Smil, 1993; Kharin et al., 1999). Water scarcity in the agricultural sector, particularly in Northeast China, has been attributed to declining pre-cipitation rates, overuse of groundwater as well as deteriorating irrigation structures and inappropriate water management. In 1999 39.7% of the available cropland including the major part of the rice based cropping systems in China was irrigated (FAO, 2002), either to increase or stabilize yields or to make cropping possible in arid regions that otherwise offer favourable cropping conditions (Fig. 1). Irrigation allows obtaining potential maximum yield while rain fed crop yields are

Table 1
Cropping systems in China according to thermal requirements and altitude

Cropping zone name	Abbreviation	Accumulated temperatures ≥10 °C	Altitude <1500 m		Altitude ≥1500 m	
			Harvests/a	Cropping system	Harvests/a	Cropping system
Cold	RL	800–1500	–	Range land	–	Range land
Cold temperate	W	1500–<3200	1	Wheat	1	maize
Warm temperate	RW	3200–<4500	1.5	Rice/wheat	1.5	Maize/wheat
Northern subtropical	RR	4500–<5000	2	Rice/rice	1.5	Rice/wheat
Southern subtropical	RRW	5000–<7000	2.5	Rice/rice/wheat	1.5	Rice/wheat
Quasi-tropical	RRS	7000–<8000	3	Rice/rice/sweet potato	2	Rice/rice
Tropical	RRR	≥8000	3	Rice/rice/rice	–	–

Source: Ren (1985), Zhang and Lin (1992), Zheng and Newman (1986), own field work. 1.5 and 2.5 harvests signify planting in autumn with a harvest in next spring. Abbreviations indicate the cropping system (e.g. RW for 'rice/wheat').
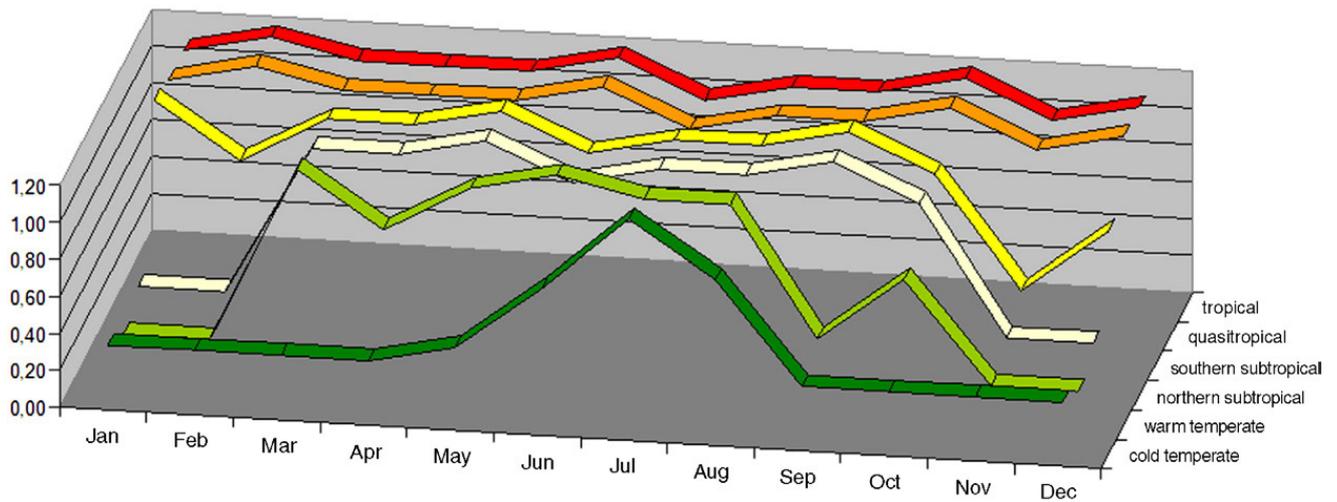
Fig. 2. Schematic representation of monthly k_C values for main lowland cropping systems in China as given in Table 1.

limited by natural moisture supply. A key question is how much irrigation water is actually necessary under present and future climatic conditions to support the Chinese agriculture. With a population expected to reach 1.4 billion in 2030 (Men, 2005) the capacity to supply

irrigation water is the key to future sustained or even extended agricultural production.

A number of studies have attempted to model the effects of climate on Chinese crop production (e.g. Chen et al., 1992; Hulme et al., 1992; Zheng, 1994; Fischer
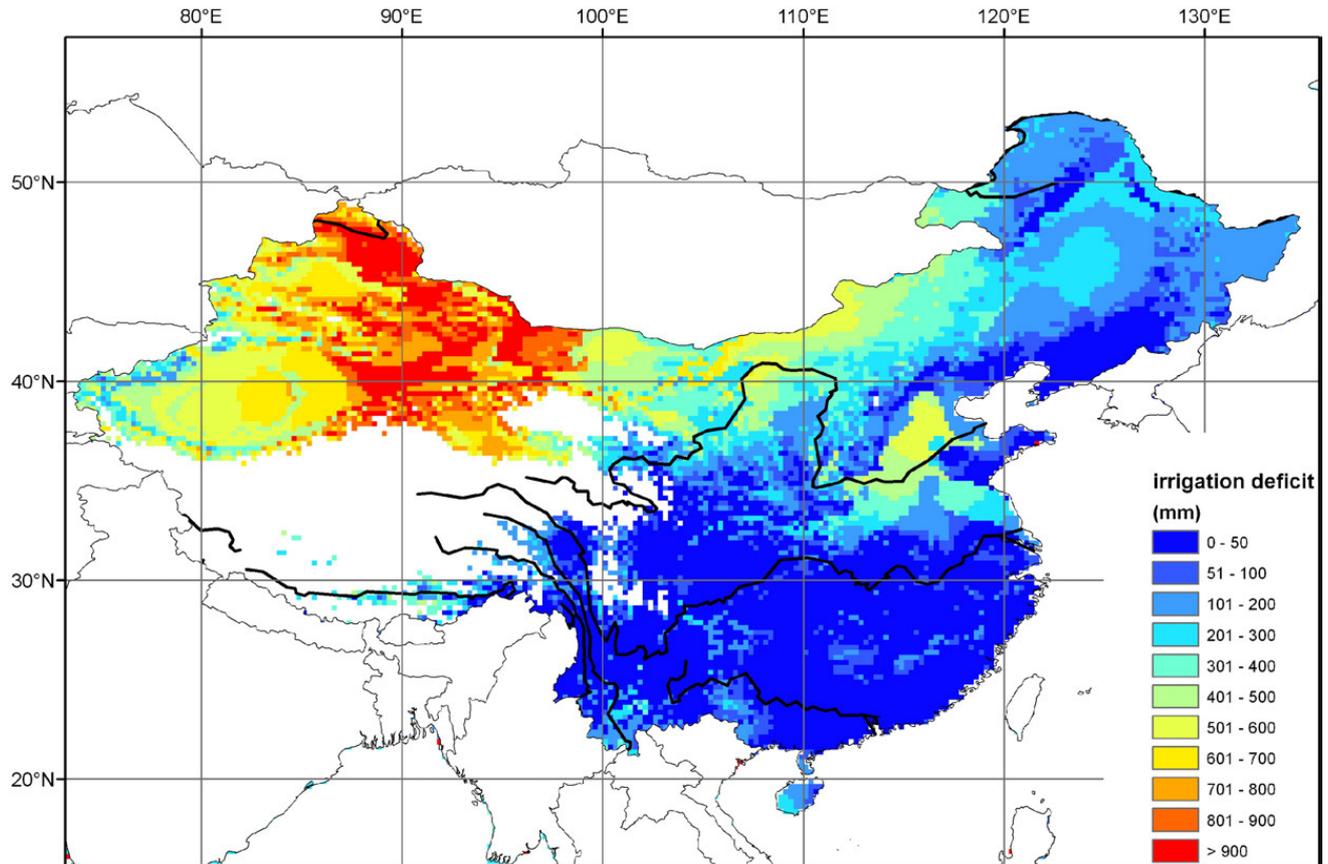
Fig. 3. Spatial distribution of the irrigation demand for the SMEAN scenario (1951–1990) of the 'main crop'. Major rivers in China are shown.

et al., 2000; Heilig et al., 2000; Tao et al., 2003a). Simulating the effects of changes in water balance components (precipitation, evapotranspiration and soil moisture) on crop production patterns depends strongly on the climate data available. In this respect the majority of the available gridded climate data show considerable shortcomings. They either have a coarse resolution (>0.5°), are based on a limited number of climatic stations or have been interpolated with statistical methods that fail to properly represent the effects of topography on the three-dimensional spatial variation of climate. As the major part of China consists of hilly to mountainous terrain it is mandatory to use climate data grids that incorporate variations due to topographical effects such as orographic precipitation or rain-shadow areas in order to arrive at realistic results. The same applies to interannual climatic variability. Year to year variations are of a much higher concern to farmers than average conditions which are implied with the use of long term average climate data in most of the cited studies. In addition evapotranspiration estimates are in many cases calculated from low-quality gridded data resulting in questionable evapotranspiration estimates. The use of simple temperature based evapo-

transpiration estimates or the generalized representation of wind speed in the calculation procedure is a particular concern as wind is a key component of the evaporative environment of many regions in China (Thomas, 2000a; Chen et al., 2005; Chen et al., 2006; Wang et al., 2006).

This study presents the results of water balance calculations for China with high-resolution gridded climate data sets that overcome the limitations described above. To estimate changes in potential irrigation demand climatic scenarios are developed from observed trends rather than from GCM results. Particular emphasis is put on the effects of interannual climatic variability in the scenarios.

2. Data and methods

To assess cropping conditions either climate data generated by General Circulation Models (GCM) or observed climate data or a combination of both have been used. GCM data typically have a low resolution of several degrees, lack both the spatial and temporal precision necessary for detailed regional analyses and in many cases have problems simulating even present-day climate
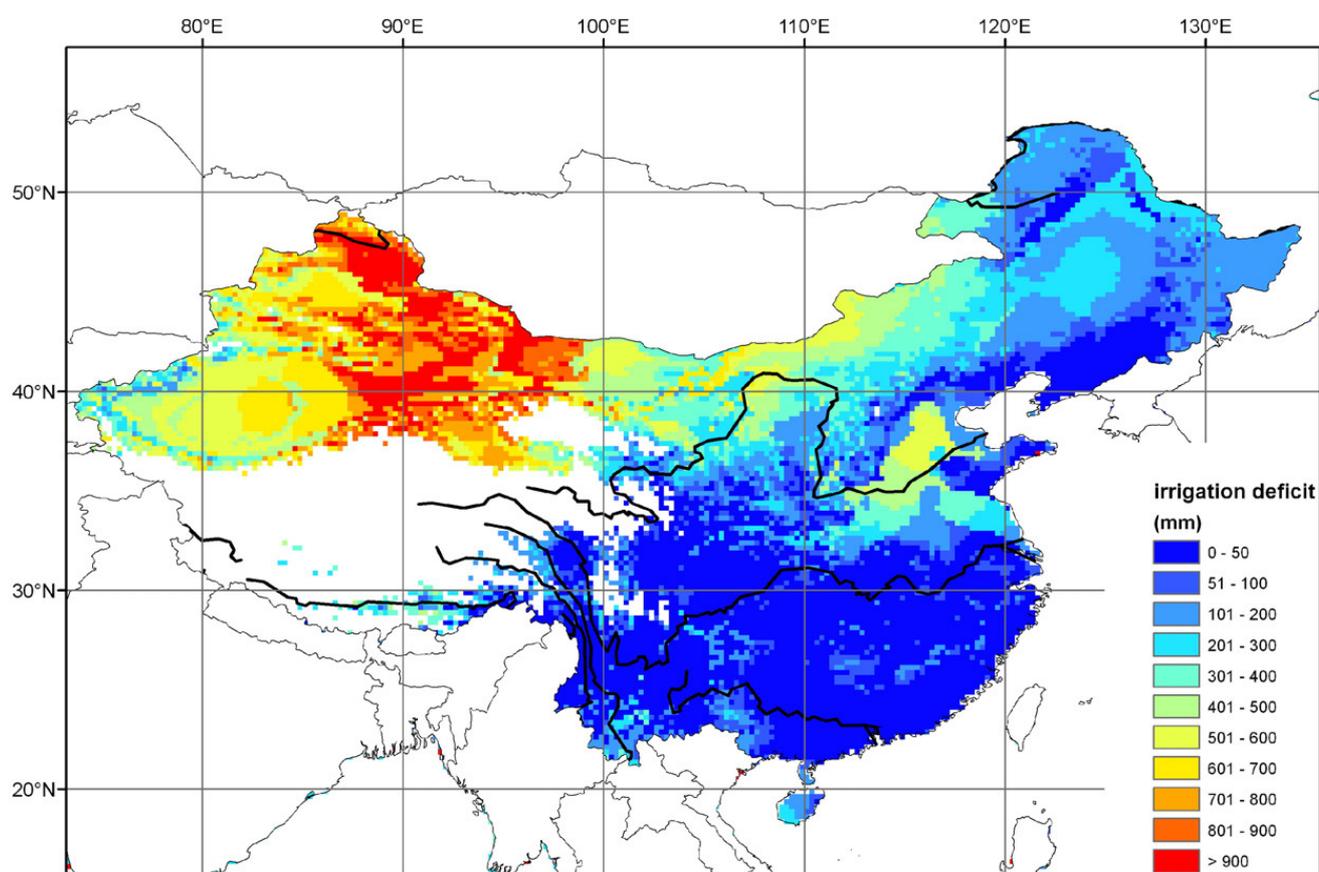
Fig. 4. Spatial distribution of the irrigation demand for the 'worst case' SMEAN$_L$ scenario (1951–1990) of the 'main crop'. Major rivers in China are shown.

(Bonan et al., 2002). In a review of 10 GCM summer monsoon precipitation data fields of East Asia neither the spatial distribution nor the amount of summer monsoon precipitation (known as 'Mei-Yu' rains) across eastern China could be reliably reproduced (Kang et al., 2002). Evpotranspiration estimates derived from GCMs are regarded as extremely unreliable (Palutikof et al., 1994) leading Chattopadhyay and Hulme (1997, 71) to state that "the results from GCM experiments should be regarded as exploratory and provisional". Climatic variations induced by the topography are in general not captured due to the low resolution of the underlying digital elevation models (Beniston, 2003). Only with the development of high-resolution GCMs or improved downscaling methods will GCM data be a useful alternative for regional studies in the future. Consequently climate data fields derived from observed climate data have been used.

2.1. Study area

China is located at the eastern margin of the Eurasian continent. Due to its large latitudinal extent (15° N–53° N) all major climates with the exception of the inner Tropics, subpolar and polar climates are found in China. Under the

climatic influence of the East Asian monsoon system summer months receive about 50–80% of the annual precipitation that varies from less than 50 mm in the western deserts to more than 2800 mm at the southeastern coast. Annual potential evapotranspiration rates from 500 mm in central China to more than 2800 mm in western China also peak in summer but are more evenly distributed throughout the year. Eastern China is dominated by a warm and moist monsoonal climate in summer while towards the north and the west precipitation decreases. Semiarid, continental conditions with cold winters limit crop cultivation in Northern and Northeastern China. Arid conditions prevail in Northwest China culminating in the desert regions of Western China. Mountains and high-altitude plateaus cover about 80% of the land area; the Tibetan Plateau is the largest contiguous mountain plateau of the world. Only about 10% of the total land area of China is usable for agriculture.

2.2. Data

Monthly climate data fields of temperature, precipitation and potential evapotranspiration (PET) gridded at 0.25° resolution for the period 1951–1990 covering East
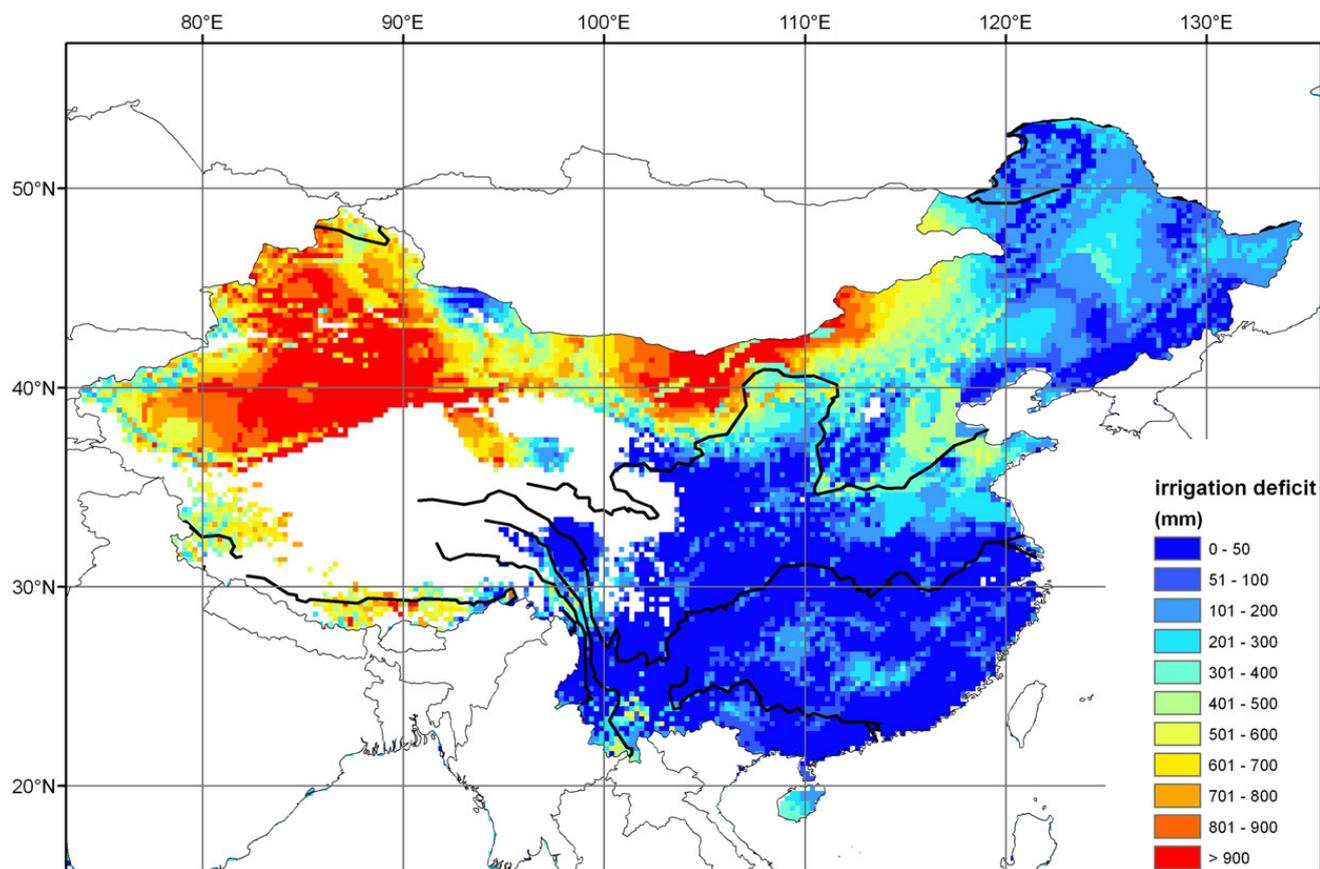
Fig. 5. Spatial distribution of the irrigation demand for the S2030 scenario of the 'main crop'.

Asia (15°N, 65°W to 55°N, 135° W) have been used in this study (Fig. 1). The data fields were generated with the REGEOTOP method that combines multivariate statistical and geostatistical principles to interpolate data fields from climate data observed at meteorological stations. The influence of topography on climatic spatial variability is taken into account by relating observed climatic values to position and topography surrounding each station. Topography is represented in the form of 'base topographies' which are statistically independent relief forms that are derived from a digital elevation model of the study area with the help of a principal component analysis. Regression analysis and geostatistics are then used to calculate final data fields based on a comprehensive climate data base covering the PR China and neighbouring countries containing time series of more than 600 and 500 station for precipitation and temperature, resp. Monthly estimates of PET were calculated with the Penman–Monteith approach (Allen et al., 1998) for 196 stations within the borders of the PR China. Details of the method can be found in Thomas and Herzfeld (2004).

Total available soil water (SW, in mm/m soil depth) was estimated from soil texture data provided by the FAO digital soil map of Eurasia (FAO, 2000) using the values given in Doorenbos and Kassam (1986). The vector data of the FAO map were resampled to a 0.25° grid.

2.3. Methods

To estimate soil water conditions and potential yield a water balance model based on the FAO Agro-Ecological Zones methodology (FAO, 1978; Fischer et al., 2000) was used. The model assumes an undifferentiated one-layer soil moisture storage and calculates soil moisture content in monthly time steps from plant specific evapotranspiration, precipitation and residual soil moisture of the previous month. Details of the method are given below. Compared to other studies that are based on FAO methodology the approach presented here integrates less agronomic constraints but offers superior spatial resolution, a realistic spatial distribution of climate data allowing for the influence of topography, the use of time series as compared to mean values and a detailed view on the effects of both long-term and inter-annual climate variability on multiple cropping systems in China.
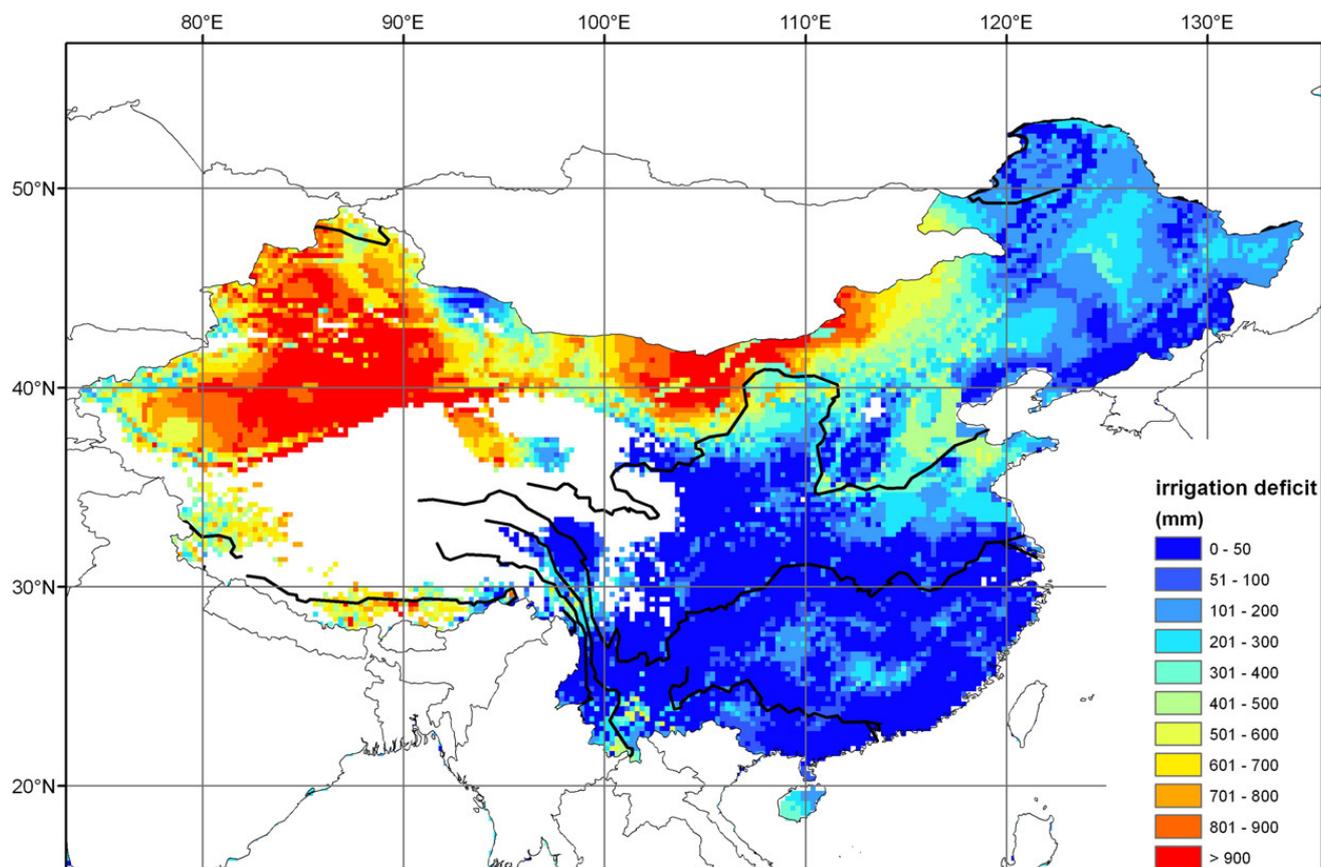
Fig. 6. Spatial distribution of the irrigation demand for the 'worst case' S2030$_L$ scenario of the 'main crop'.

2.3.1. Phenology and cropping systems

In China a variety of cropping patterns are in use that are adapted to the local climatic conditions. To simulate realistic cropping patterns potential cropping zones were delineated based on accumulated temperatures (Table 1). To each potential cropping zone a typical combinations of field crops were assigned based on information by Ren (1985), Zhang and Lin (1992) and Zheng and Newman (1986). For mountainous regions above 1500 m separate cropping patterns (Thomas, 2000b) were selected to account for the delayed response of crops to lower thermal resources. Regions with accumulated temperatures from 800–1500 °C are primarily suitable as range land and were not included in the water balance calculation. In the quasi-tropical zone sweet potato was selected as a proxy for several field crops which are grown in combination with rice.

In order to allow a detailed understanding of cropping conditions water balances were calculated separately for each crop in multiple cropping systems, giving up to three results per growing season in the quasi-tropical and tropical zone.

Accumulated temperatures and begin and length of the growing season (BGS and LGS, resp.) were determined based on the number of months with temperatures above 10 °C for each grid node location. BGS and LGS are used to scale crop coefficients and rooting depths that determine potential water consumption by the crop.

The maximum water demand by the crop is described by maximum crop evapotranspiration (ET_m). ET_m increases from planting, reaches a maximum during flowering and decreases during the maturity stage. ET_m is related to PET as

$$ET_m = PET * k_C$$

where k_C is the crop coefficient for the specific phenological stage. k_C values were taken from Doorenbos and Kassam (1986) and interpolated according to the duration of the phenological phase in relation to calculated LGS with the help of a cubic spline. During fallow periods and winter dormancy of winter wheat k_C values of 0.2 and 0.3, resp. were assumed (Fig. 2). Rice cultivation in regions above 1500 m are corrected for prolonged seed bed periods (He, 1981) and slower development at higher altitudes (Li and Liu, 1988). Possible intercropping or relay cropping has not been accounted for.

Similar to plant transpiration rooting depth (RD) increases with plant life until it reaches a maximum
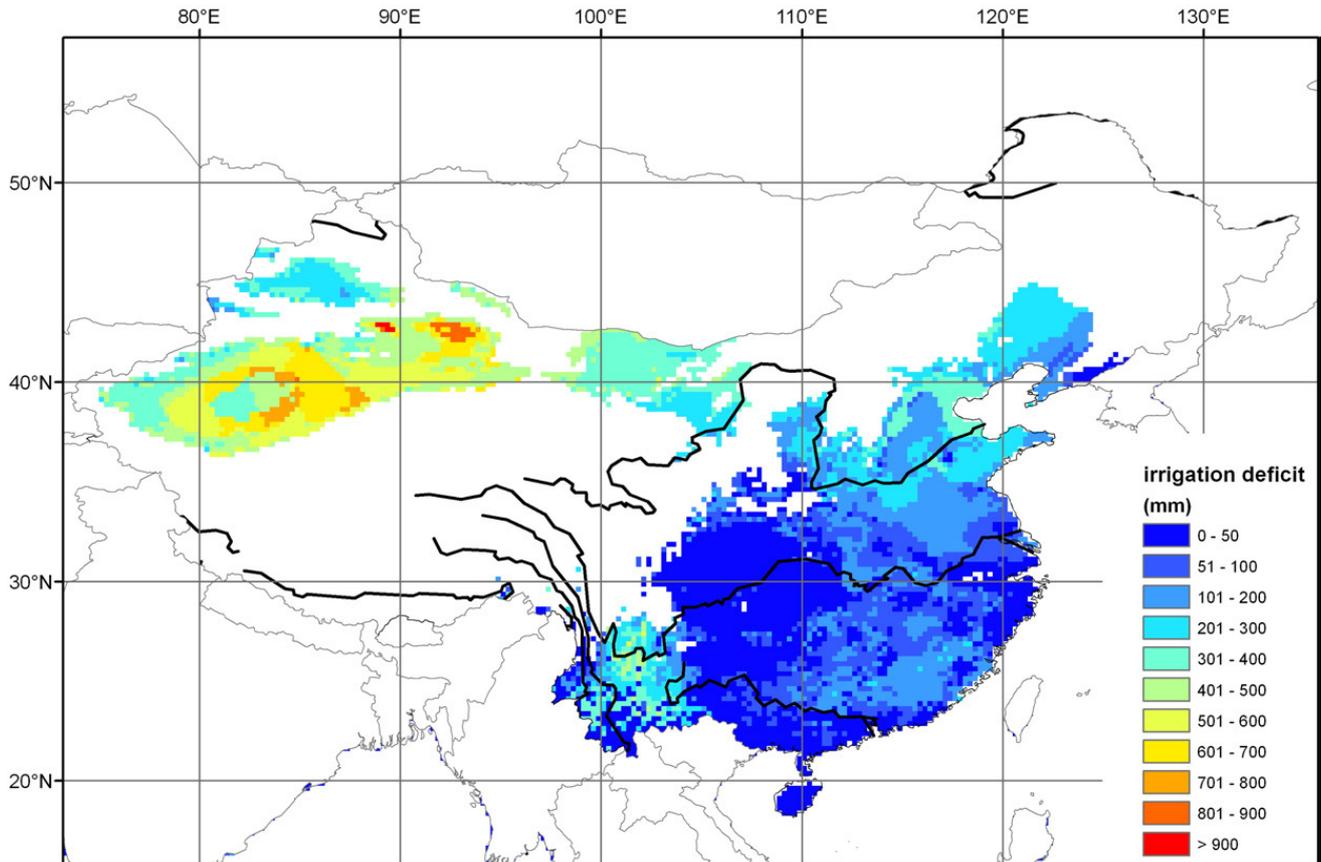
Fig. 7. Spatial distribution of the irrigation demand for the SMEAN scenario of the 'second crop'.

during the maturity stage. Rooting depth determines the amount of soil water actually available to the plant (maximum plant available soil water SW_m) as a fraction of SW. Rooting depths vary considerably with crop species and phenological stage. Setting a fixed rooting depth independent of crop and phenological stage instead using plant specific and development dependant values can severely under- or overestimate plant available soil water (Frére and Popov, 1979). In addition plough soles in wetland rice cultivation often limit rooting depths for rice to 0.3 m and pose a problem for winter wheat in rice–wheat cropping systems (Timsina and Connor, 2001). Consequently maximum rooting depths of rice and wheat were restricted to 0.3 m in all rice based cropping systems and to 1.0 m for wheat in rice–wheat cropping systems, resp. Rooting depths for other crops were taken from Smith (1992). Rooting depths were interpolated the same way as k_C values.

2.3.2. Calculation procedure

The water balance was calculated for each grid node on a monthly basis for the period 1951–1990. For each growing season the potential cropping zone of each grid node was determined. Monthly k_C and RD values were interpolated according to BGS and LGS of the cropping system in the respective year. Monthly SW_m was calculated from SW and RD as

$$SW_{mi} = SW_i*RD_i$$

with i as the index of the month.

Compared to the original FAO concept developed primarily for tropical and subtropical regions the potential delayed contribution of winter precipitation to the soil water balance in the form of snow melt (SM) has been introduced. Precipitation at temperatures <0 °C is regarded as snow and is summed up separately. The use of the PET concept is of limited value under such conditions as the assumptions of conditions similar to a green grass cover are violated. Direct evaporation from the snow cover is based on empirical observations and is accounted for as

$$ET_S = k_S*PET$$

with ET_S as monthly snow evaporation total, PET as monthly PET total and k_S as an empirical conversion factor set to 0.3 as the average value for snow covered surfaces in China (Zheng, 1994).
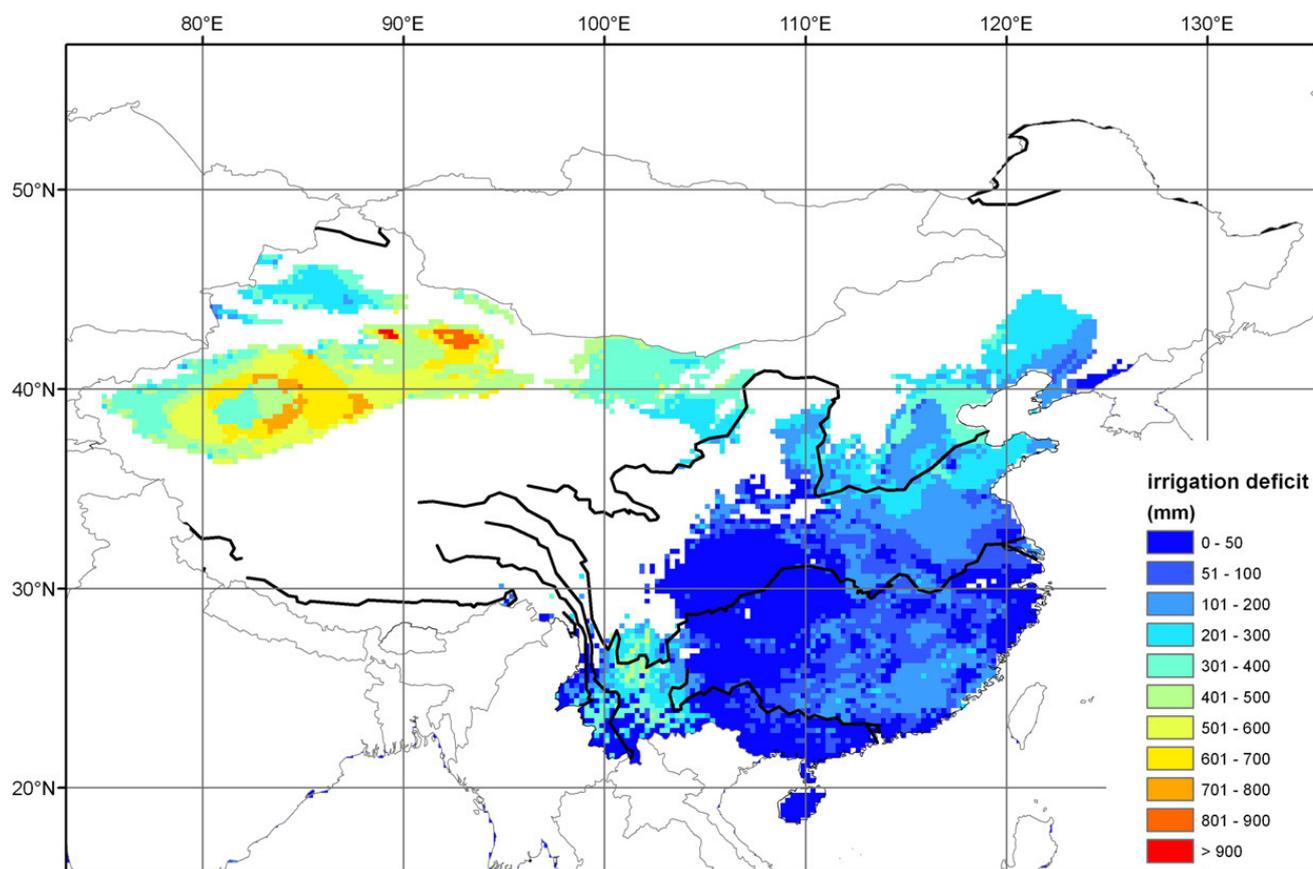
Fig. 8. Spatial distribution of the irrigation demand for the 'worst case' $SMEAN_L$ scenario of the 'second crop'.

Monthly melt rates SM were calculated according to Fischer (1997) as

$$SM = 165 * T^{-1}$$

with T as monthly temperature >0 °C.

Not all measured precipitation is directly usable by the plant. To allow for effects of crop interception and run-off effectiveness of precipitation (Dastane, 1974) was set to 0.9 giving effective precipitation (P_e) as 90% of observed monthly precipitation values. Lateral as well as vertical water movements in the soil were not accounted for as their spatial variability within the 0.25° grid cells is not known and the temporal variability is too high to represent them correctly at this scale (Henderson-Sellers, 1996).

To initialise the soil water balance calculations for the first year were run twice assuming that after one year soil water conditions in January are representative of actual conditions. Monthly soil water content was calculated as

$$SW_{ai} = SW_{ai-1} + P_{ei} - ET_{ai} + SM_i$$

with SW_a as actual soil water, ET_a as actual evapotranspiration, SM as snow melt and i as the index of the month (1,2,3,..., 11,12). ET_a is determined based on the contribution by precipitation, snow melt and residual soil moisture of the preceding month. If ET_m surpasses the available water supply in month i

$$ET_{mi} > SW_{ai-1} + P_{ei} + SM_i$$

ET_{ai} is set to the total amount of available water:

$$ET_{ai} = SW_{ai-1} + P_{ei} + SM_i$$

If ET_m is lower than the available water supply

$$ET_{mi} \leq SW_{ai-1} + P_{ei} + SM_i$$

then ET_a is set to be equal to ET_m

$$ET_{ai} = ET_{mi}$$

with the surplus assumed to be lost by run-off.

At the end of a growing season the relation between total crop water demand $\Sigma\ ET_m$ and total crop water supply $\Sigma\ ET_a$ gives an information about the magnitude of a possible water deficit. The irrigation demand ID
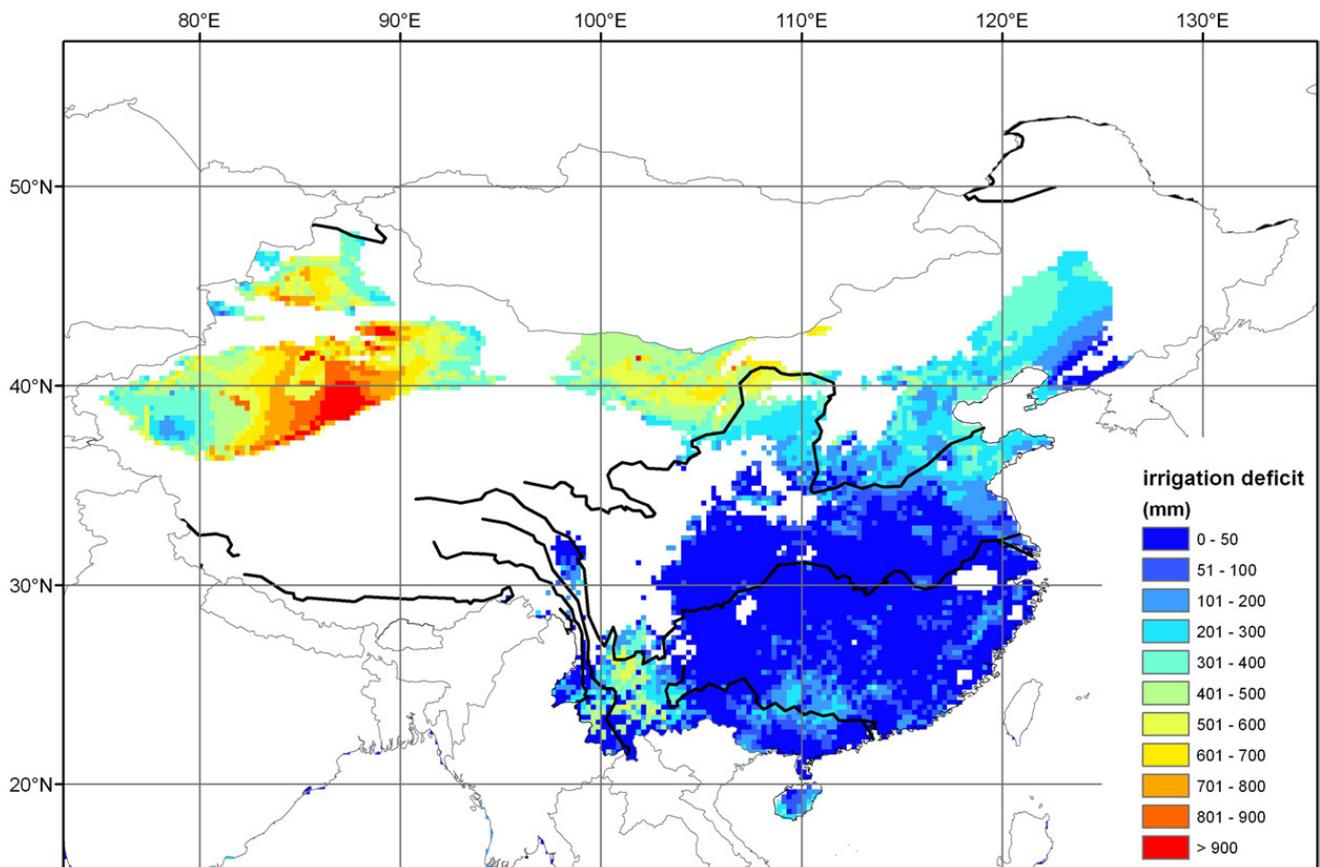
Fig. 9. Spatial distribution of the irrigation demand for the S2030 scenario of the 'second crop'.

expresses to which extent the crop has experienced a water deficit and is defined as

$$ID = \Sigma ET_m - \Sigma ET_a$$

giving the amount of irrigation water necessary to obtain maximum yields with ΣET_m and ΣET_a as ET_m and ET_a totals over the growing season, resp.

2.3.3. Representing interannual climatic variability

Most climate change studies have focussed on changes in the mean climatic conditions that represent long term averages. Changes in climatic patterns should however reveal themselves rather in changes of the extreme values (Katz and Brown, 1992). Extreme events (droughts or floods) are more important for farming operations than average values which in some climates with large interannual variability may never occur in reality. The same applies to trends of annual means of precipitation and temperature that have been used to describe cropping conditions (e.g. Hulme et al., 1994; Schäfer, 2001). Most crops are however grown during the summer season so that annual trends are not representative. In addition winter and summer trends often show opposing signs canceling each other at least partially when annual trends are considered. As a result annual trends have a low significance for agricultural purposes (Smit and Yunlong, 1996).

Oldeman and Frère (1982) proposed to use the probability of exceedance to study the impact of interannual precipitation variability on crop production. The probability of exceedance, however, is based on a normal distribution and is a poor indicator particularly for precipitation probabilities in many regions in China where strongly skewed or bimodal distributions are observed. Instead the use of the decile difference DD defined as:

$$DD = D90 - D10$$

is proposed where D90 and D10 are the upper and lower deciles of a distribution, resp. DD defines the range of values that have occurred in 80% of the observed years and gives a more precise representation of climatic variability than parametric variability measures that rely on a normal distribution. To investigate if and to which extent interannual climatic variability has changed trends of DD over the period 1951–1990 have been prepared.
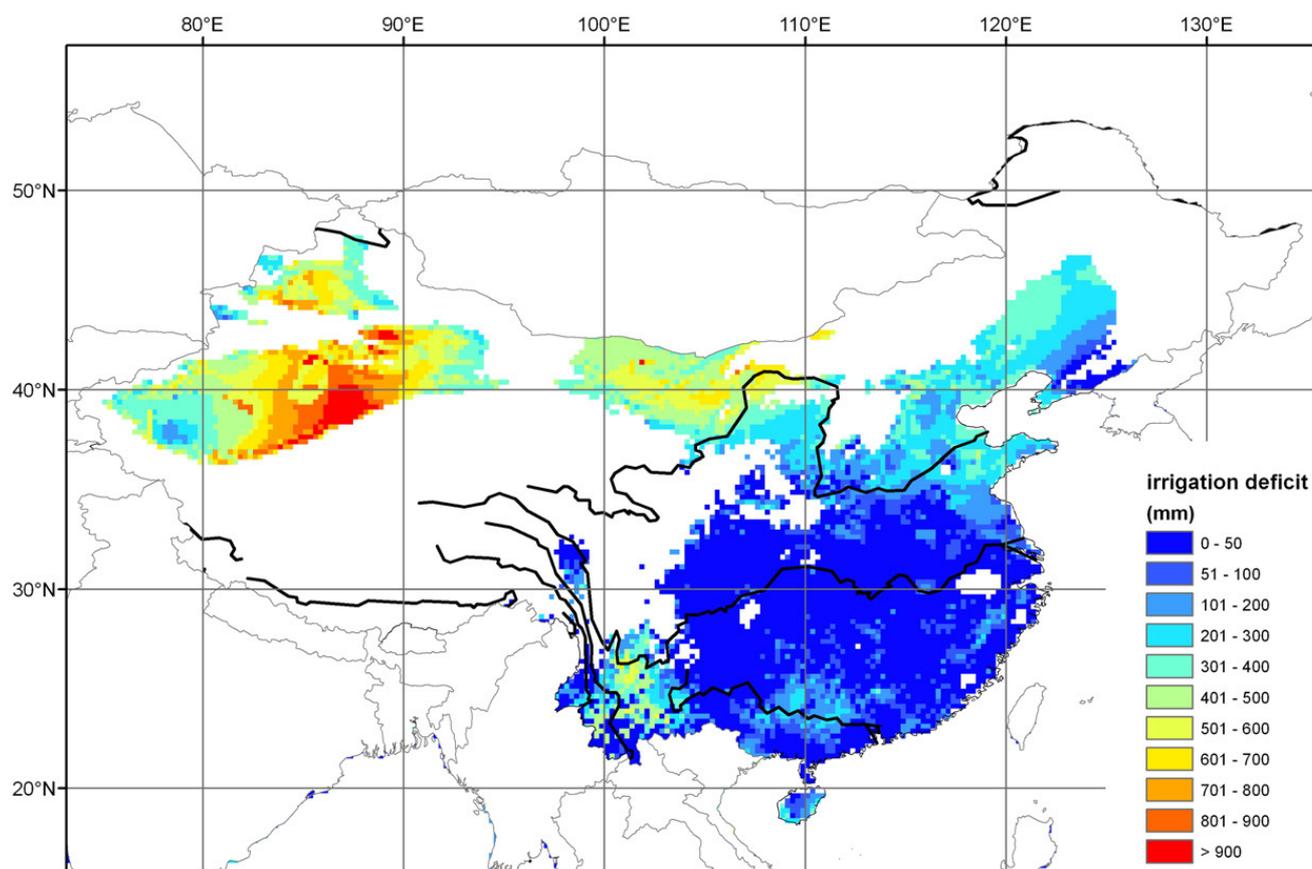
Fig. 10. Spatial distribution of the irrigation demand for the 'worst case' S2030$_L$ scenario of the 'second crop'.

DD is extracted from sub samples contained in moving windows of 10 yr width (i.e. 1951–1960, 1952–1961... 1981–1990) from the monthly time series for each grid node. Arranged in sequential order they represent a time series of interannual variability for which in turn a trend can be extracted. Linear regression was used to calculate DD trends.

2.3.4. Definition of climate scenarios

To describe recent and possible future cropping conditions different sets of climate scenarios are developed from observed time series and trends. Instead of using the results of GCMs to extrapolate recent climate data fields into the future (e.g. Tao et al., 2003b) climatic scenarios are derived from observed trend values. Trend-based scenarios assume that regional circulation patterns will remain stable over the predicted time period leaving the corresponding spatial distribution namely of precipitation and PET unaltered. While only GCM results can be expected to give physical based predictions of future climates observed climate trends may stand as indicators of future climatic conditions provided observed trends represent stable long-term climatic conditions. An anal-

ysis of all possible observation periods (combinations of observation duration and begin) has shown that the majority of climatic trends in China have remained stable from 1951 to 1990 (Thomas, 1999) supporting the idea that observed climatic trends can be used to develop climate scenarios.

Each set of climate scenarios consists of a mean scenario and an extreme scenario. The mean scenarios are based on the mean conditions observed or predicted for the years 1951–1990 and 2030 (SMEAN and S2030, resp.). Climate data for the S2030 scenario are extrapolated from regression trends derived from the 1951–1990 gridded time series climate data:

$$S2030 = SMEAN + (t * Tr_A)$$

where S2030 denotes extrapolated monthly values for the year 2030, SMEAN observed mean monthly values for the period 1951–1990, Tr_A annual trends of observed monthly climate values for the period 1951–1990 and t the number of years between the temporal mean of the 40-yr time series and the scenario. As the temporal mean of the time series corresponds to 1970 t equals 60 yr.
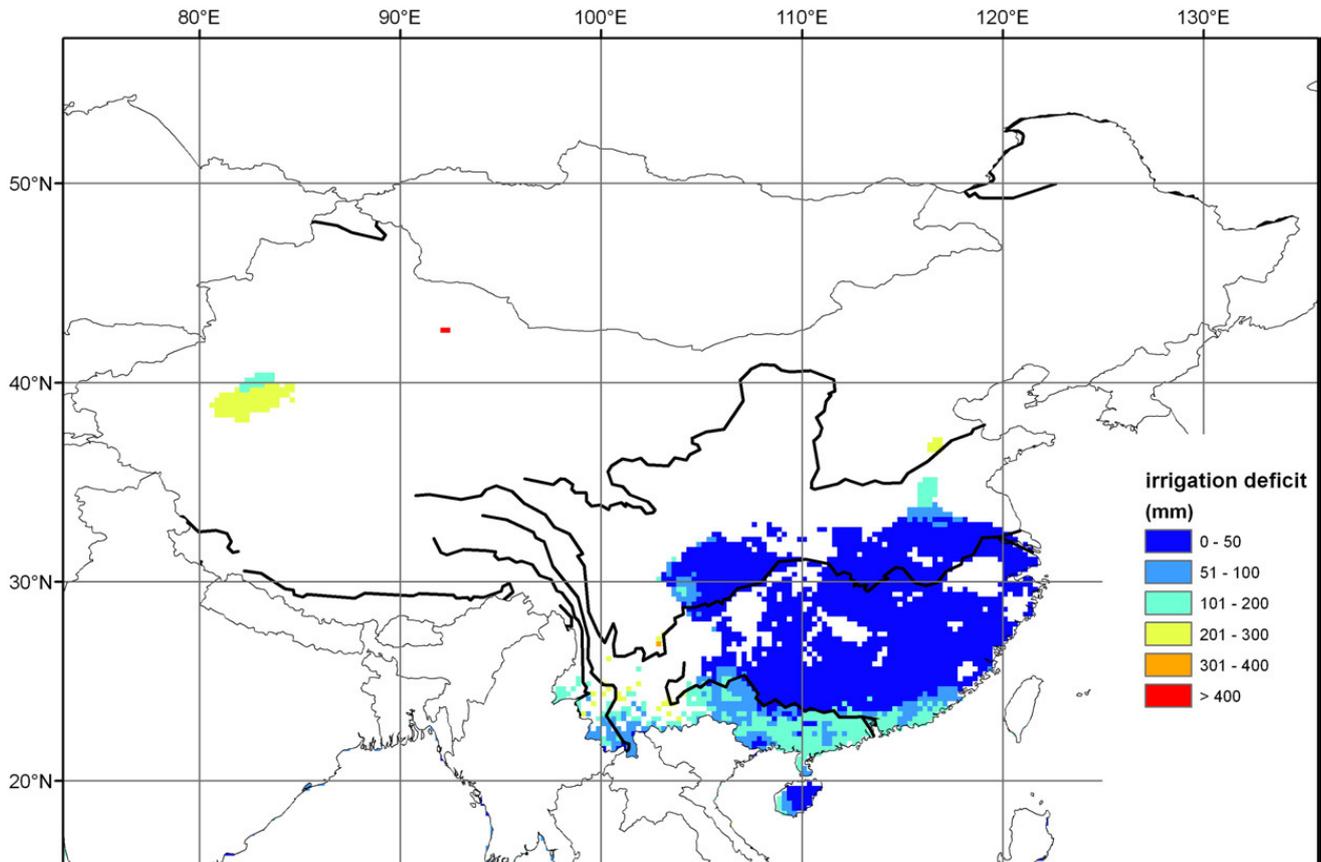
Fig. 11. Spatial distribution of the irrigation demand for the SMEAN scenario of the 'third crop'.

Extreme scenarios represent artificial 'worst case' (arid) climatic conditions. Each extreme scenario is based on the respective mean scenario minus observed or extrapolated lower ($SMEAN_L$ and $S2030_L$) boundaries of variation as described by DD values or DD trend values, resp.

$$SMEAN_L = SMEAN - DD/2$$

$$S2030_L = S2030 - (t*DDTr_A)/2$$

with $S2030_L$ as extrapolated lower values for the year 2030, resp. and $DDTr_A$ as annual trends of observed monthly DD values for the period 1951–1990.

Water balances of the S2030 scenario are calculated based on 12 mean monthly values while the SMEAN scenario represents the mean results of the 40-yr time series. Potential cropping zones were calculated based on BGS and LGS derived from each of the 4 scenarios in order to identify possible spatial changes in the cropping patterns.

The resulting scenarios depict both temperature and humidity related effects on agricultural production.

Temperature defines BGS and LGS and therefore the possible cropping system as well as the potential extent of arable areas of each cropping system. Precipitation and PET and in turn the water balance allow to estimate ID for maximum yields. Where climatic conditions allow multiple cropping systems separate ID values are obtained for each crop. No effort has been undertaken to allow for other factors that may limit the extent of irrigated agriculture such as topography or water availability for irrigation. ID values are shown for all areas where climatic conditions for the given cropping zones are satisfied.

3. Results

With up to three crops possible in the tropical and quasi-tropical zones of China each crop is depicted in separate maps to allow a better representation of spatial features. Crops are identified as main, second and third crop according to the cropping system columns in Table 1. The main crop is defined as the crop usually sown with the onset of the monsoon season in late spring or early summer. The growing season of the second crop depends
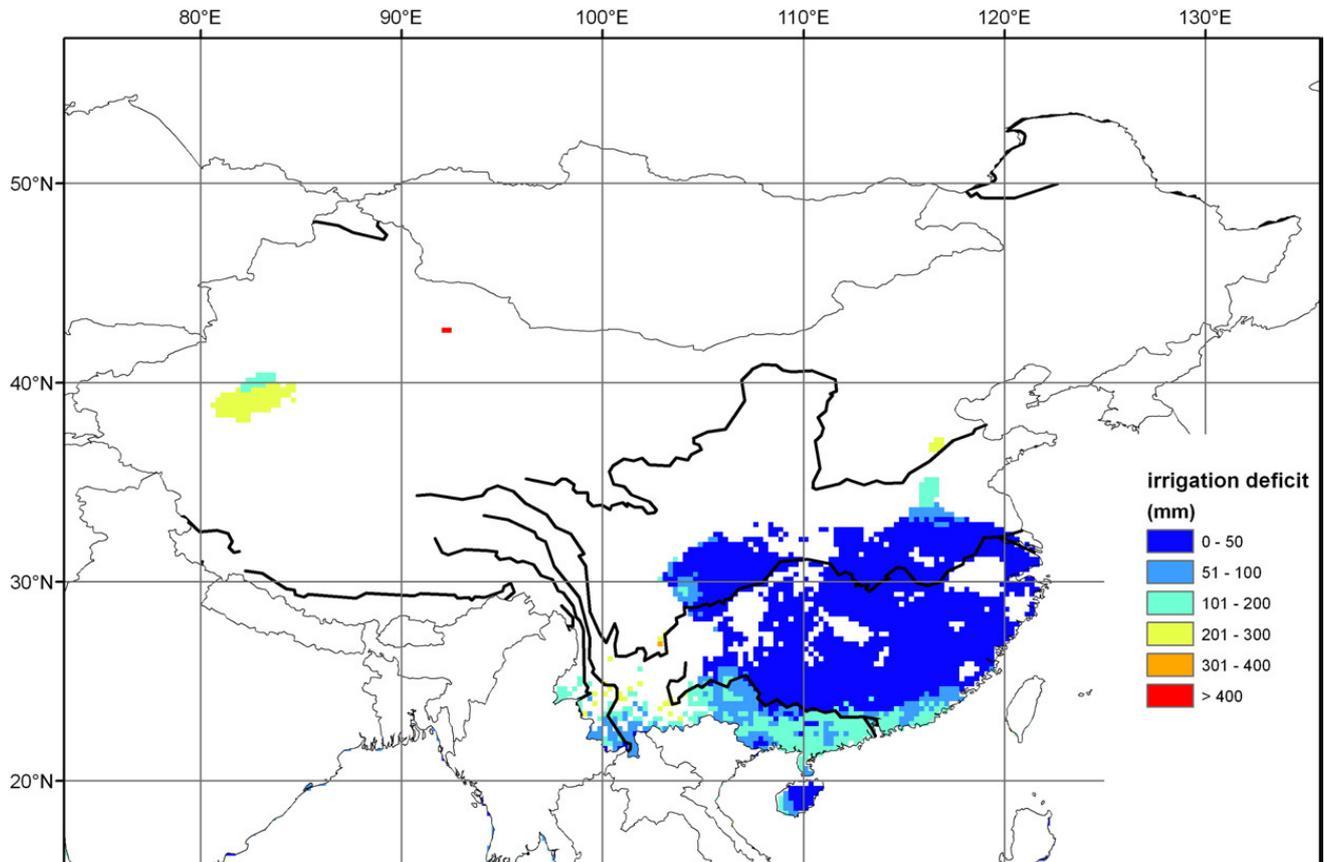
Fig. 12. Spatial distribution of the irrigation demand for the 'worst case' $SMEAN_L$ scenario of the 'third crop'.

on the crops being grown in the south-subtropical to tropical zone (double or triple cropping system, rice planted in late summer or autumn) or in a north-sub-tropical or temperate double cropping system (winter wheat sown in late autumn and harvested next spring). The results of both cropping systems are presented in the same map. Regions that are climatically unsuitable for agriculture are not discussed.

3.1. Present conditions (SMEAN scenarios)

For the main cropping season in summer Fig. 3 shows a clear distinction between the eastern and southern regions of China where ID is low (<100 mm) and the western and northern sectors where ID may exceed 400 mm. A noteworthy feature is the small isolated region of high ID in the Huang He coastal plain in the otherwise humid coastal region. In Northeastern China ID may reach as high as 400 mm while in west China only the periphery of the Taklimakan desert does not surpass an ID of 500 mm. The small isolated cropping region of Southern Tibet along the Yarlung Tsangpo River (the upper reaches of the Brahmaputra) likewise

requires up to 300 mm of irrigation water in the main season.

In particularly dry years (SMEAN$_L$ scenario, Fig. 4) low ID conditions only remain in isolated pockets in southern and southwestern China. Regions north of the lower Yangtze basin, including the northeastern wheat growing region, can reach IDs of up to 600 mm. Both in western China and on the Tibetan plateau virtually all of the necessary water would have to be applied by irrigation with a seasonal water demand surpassing 600 mm.

During the second crop the SMEAN scenario shows a similar pattern with low ID values in the south and the east and high values in the west, resp., (Fig. 5). Stronger deficits of more than 200 mm occur mainly in the South-west and Northeast. In West China the Dsungar Basin shows moderate deficits comparable to those of Northeast China while along the periphery of the Taklimakan desert an ID of up to 600 mm is estimated. Under the SMEAN$_L$ scenario moderate deficits are restricted to a band south of the Yangtze and north of the Pearl river with IDs mainly ranging up to 300 mm (Fig. 6). North of the Yangtze river, but also in the immediate vicinity of the southern coast
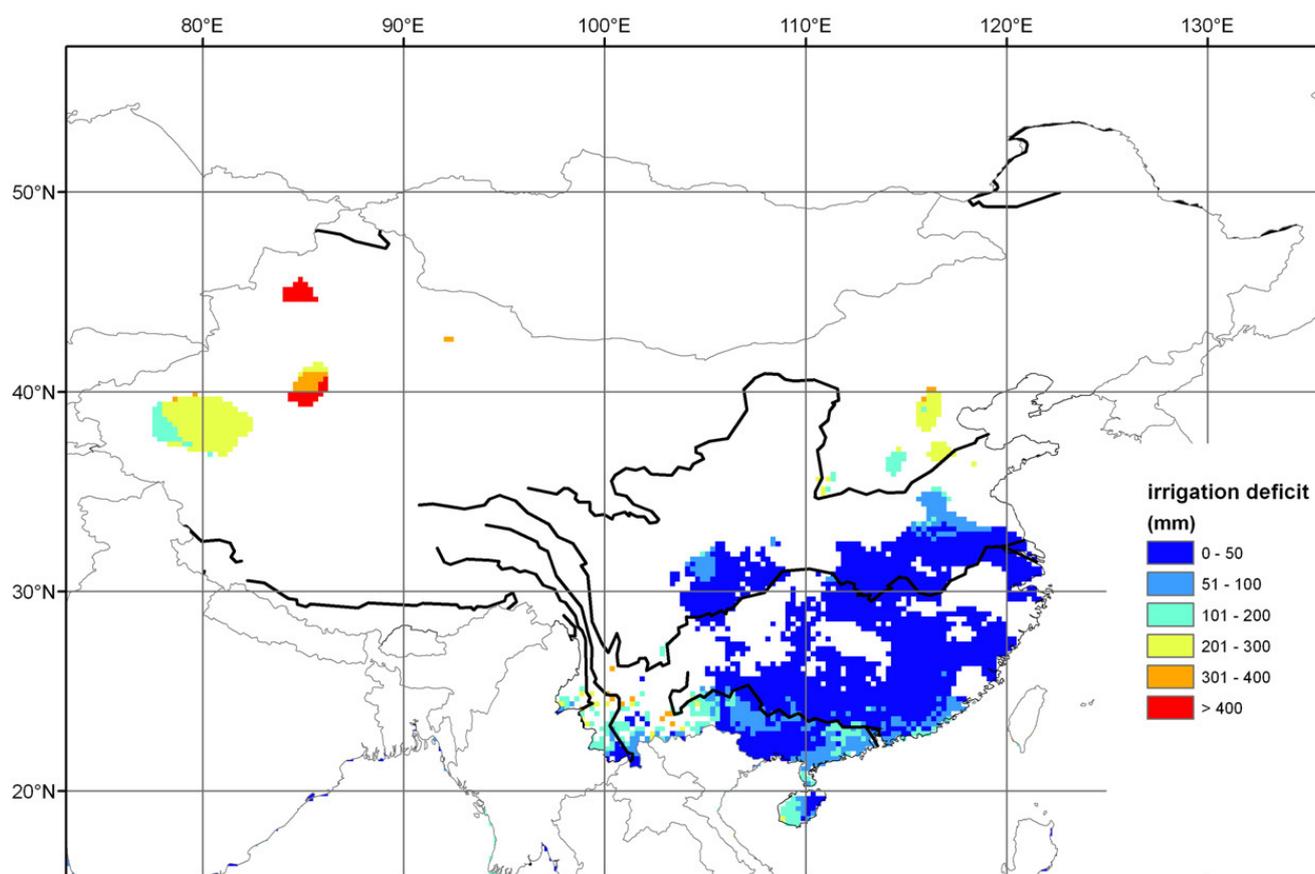
Fig. 13. Spatial distribution of the irrigation demand for the S2030 scenario of the 'third crop'.

and in Southwestern China IDs drastically increase up to 600 mm. The same applies to Western China where the lowest IDs already surpass 400 mm.

For the third crop slight deficits are found in the southern coastal region while the remaining parts of the triple cropping zone experience practically no water shortage (Fig. 7). In contrast the L scenario (Fig. 8) does not only show markedly increased IDs of up to 300 mm, particularly in the vicinity of the coast and in Southwestern China, but even in the usually drought-free Basin of Sichuan. A considerable reduction and defragmentation in overall cropping area is also visible.

3.2. Future conditions (S2030 scenarios)

For the major part of eastern China the S2030 scenario (Fig. 9) predicts conditions similar in extent and magnitude to the current situation (Fig. 3). In the Huang He coastal plain the predicted ID will decrease by about 100 mm while in Northwest China along the Mongolian border decreasing evapotranspiration trends would even allow rainfed agriculture. Water deficits in the remaining parts of Northwest China and Southern Tibet may increase with IDs exceeding 600 mm.

This trend persists in the $S2030_L$ scenario (Fig. 10) of the main season where high IDs are predicted for Northwest China as well as southern Tibet and Northeast China with IDs surpassing 700 mm. The entire southern and eastern section of China is expected to see marginally increased IDs with the southern coastal region and parts of Southwest China predicted to remain largely unaffected.

The second season sees a slight increase in cropping area compared to the SMEAN scenario (Fig. 11). IDs are predicted to decrease relatively to the present situation in Eastern China while towards the west IDs increase progressively. Within the current agricultural areas the highest IDs are thought to occur in the oasis towns along the border of the Taklimakan Desert. Again a considerable decrease of water availability is predicted for Western China in the $S2030_L$ scenario (Fig. 12). In regions north of the Yangtze river ID remains high (>300 mm). The general situation in Southern and Eastern China however appears to become more favourable with ID decreasing by 50–100 mm in general.

The situation for the third crop is expected to remain largely unaffected with a slight reduction of anticipated IDs for the southern coastal area (Fig. 13). The extent of
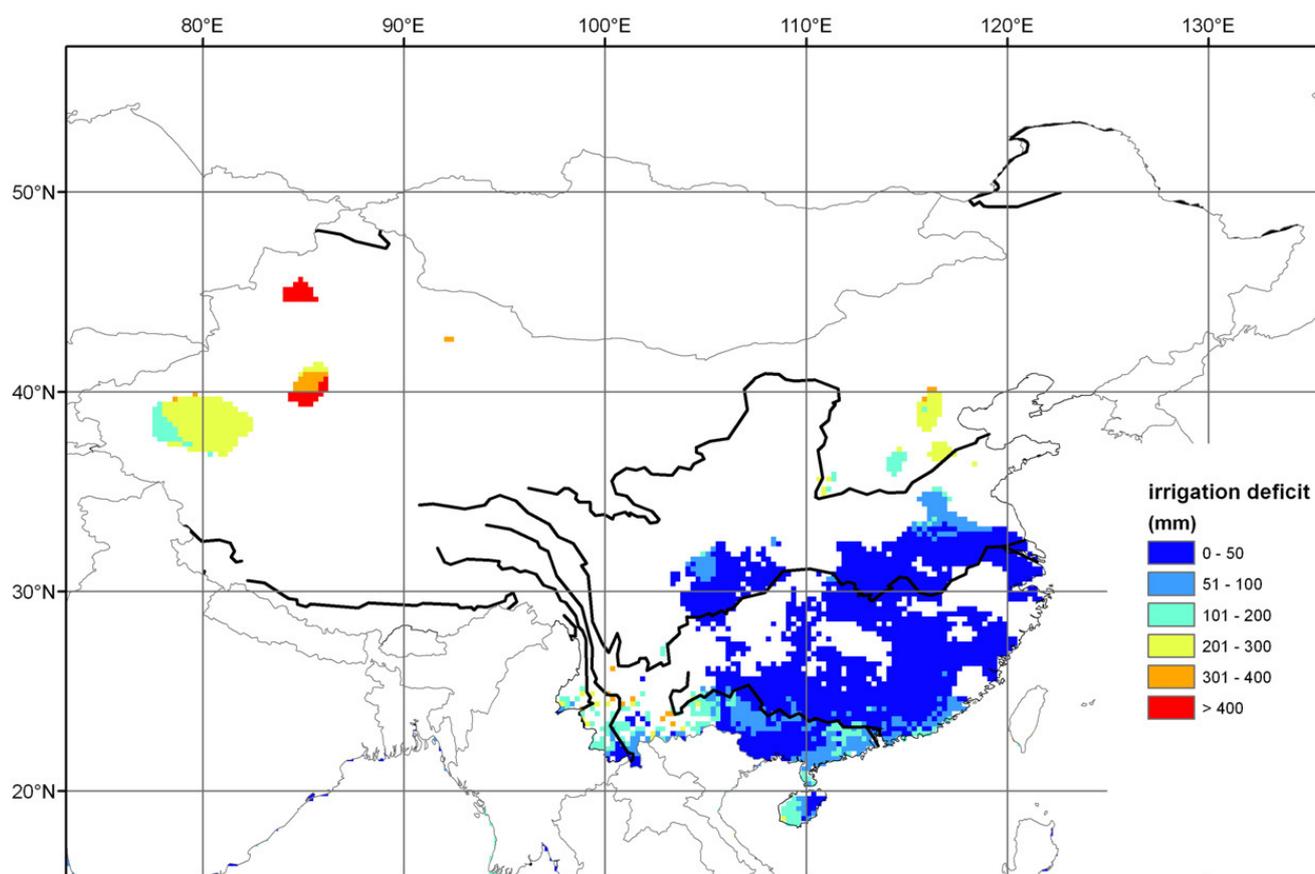
Fig. 14. Spatial distribution of the irrigation demand for the 'worst case' $S2030_L$ scenario of the 'third crop'.

the area is to decrease slightly mainly through a reduction of cropping areas in low basins. The same applies to the S2030$_L$ scenario (Fig. 14), this time however with a predicted ID increase in the lower Yangtze basin.

4. Discussion

The results show that during the last decades cropping conditions and consequently irrigation demand in China have been subject to considerable variations both due to interannual and intraannual climatic variability. The same applies to the modelling results of assumed future cropping conditions. Both temperature and moisture related effects can be identified: while temperature determines the extent of potential cropping areas moisture variations are reflected in ID values.

4.1. Temperature

Contrary to common belief temperature does not play the primary role in the estimation of PET and hence of crop water requirements. In this study temperatures have mainly been used to define LGS which in term de-

lineates potential cropping areas (Fig. 15). Indirectly temperature influences water demand as changing temperatures may allow or make it necessary to switch from one cropping system to another. The model used in this study incorporates anticipated reactions by farmers to changed environmental conditions by selecting cropping systems according LGS. A projected temperature increase would allow adjusting cropping systems from temperate rice–wheat rotation to subtropical double cropping of rice. In this case the second crop growing season shifts from fall, winter and spring (winter wheat) to late summer and fall (second rice crop) where precipitation totals tend to drop sharply at the end of the monsoon season. During this period soil moisture reservoirs are not able to sustain the crop without additional irrigation leading to sharply increased IDs. In this case the mechanistic decision for a different cropping system based on temperature information alone would lead to markedly reduced yields.

The major part of the agricultural production area of China both in terms of area and yield is part of the cropping area of the main crop. A movement of this core zone of more than 500 km to the north due to the effects
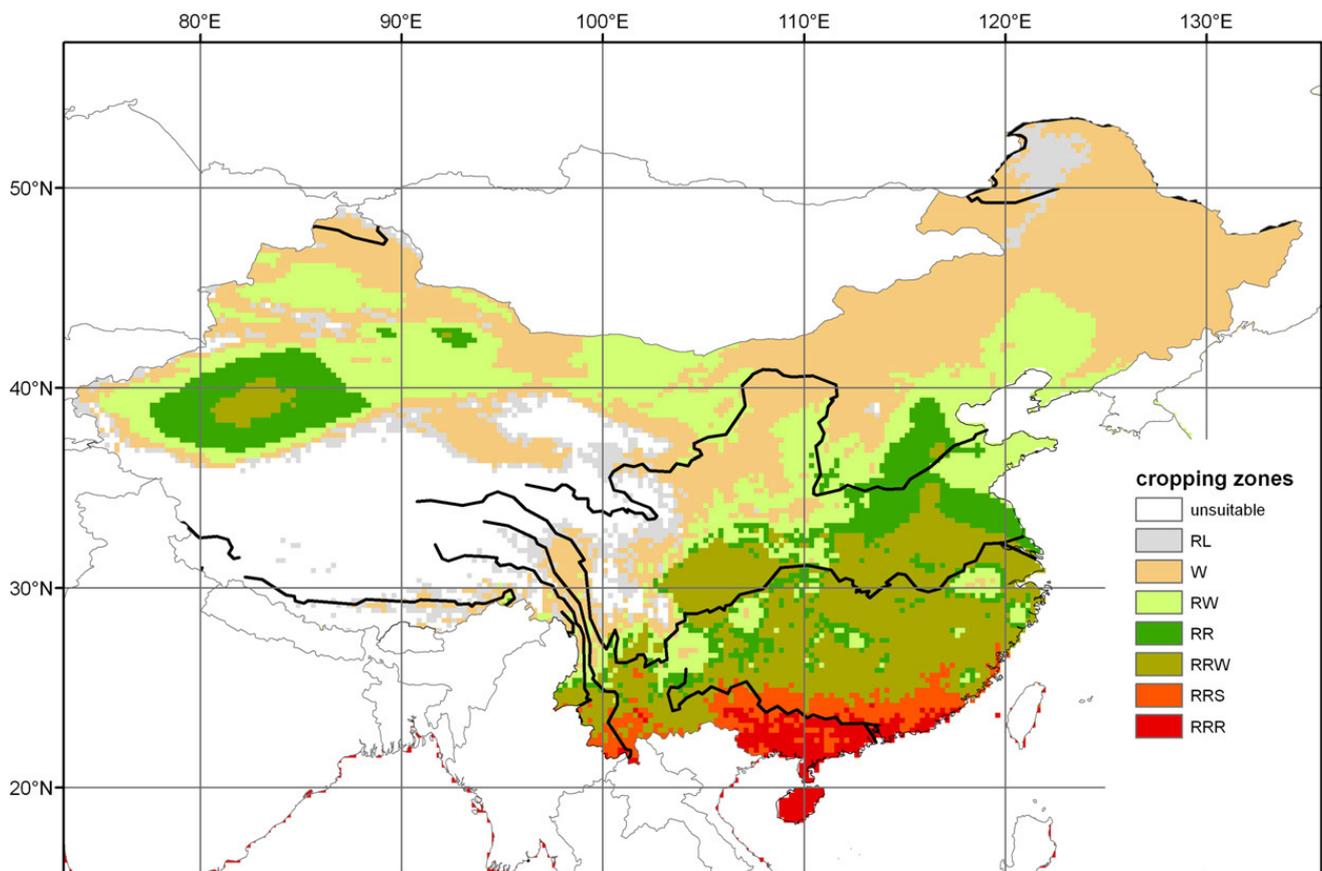
Fig. 15. Potential cropping systems for the SMEAN scenario (1951–1990), based on accumulated temperatures >10 °C. Abbreviations are given in Table 1. Blank areas represent regions climatically unsuitable for agriculture and animal husbandry.

of global warming has been predicted by GCM results (Hulme et al., 1992; Jin et al., 1994). The model results of the S2030 scenario however indicate that if present trends remain stable the displacement might be almost negligible. Present-day variation of polar boundaries of cropping zones due to interannual climatic (thermal) variability as represented by the SMEAN$_L$ scenario are far more pronounced than the anticipated northward movement of cropping zones in the S2030 scenario. Instead of a general northward migration of all cropping zones a slight expansion of the southern subtropical (rice–rice–wheat) cropping system and a dissection of cropping zones are foreseen under the given climatic trends. A stronger fragmentation of vegetation zones rather than a general northward movement is also predicted by Chen et al. (2003) for the natural vegetation of China under climate change conditions based on GCM results.

While the potential cropping areas of the main and second crop are subject to some variation in response to seasonal temperature variability it is the third crop during the winter season that is most affected. Winter temperatures in South China are controlled by erratic intrusions of cold air from Central Asia that bring plummeting temperatures and frost to subtropical and tropical regions of South China (Domrös and Peng, 1986; Zhang and Lin, 1992). While these 'cold waves' are singular events even a single outbreak can lead to wide spread frost damage and yield losses in South China down to approximately 26° N. The northern boundary of the triple cropping zone in the L scenario is more or less directly defined by the southerly extent of cold waves. The S2030$_L$ scenario predicts an intensification of the occurrence of cold waves that would leave only rudimentary cropping areas south of 25° N in extremely cold winters.

4.2. Moisture availability

Fig. 3 shows that in general China can be divided into a region south of 35° N with lower IDs (South and Central China), the region north of 35° N and east of 100° E (Northeast and North Central China) with intermediate IDs and the region north of 35° N and west of 100° E (Northwest China) with intermediate to high IDs. The southern and eastern parts of the Tibetan Plateau can be considered as a separate region that exhibits moderate to high IDs due to its high altitude. This regional distribution reflects the well known fact that the average northern extent of the monsoonal precipitation belts is restricted to areas south of appr. 40° N (Domrös and Peng, 1986). North of ∼40° precipitation

decreases (and PET increases) towards the continental desert areas of West China and western air masses begin to take over as the primary source of precipitation. Superimposed on this northward decrease of climatic water availability is the water demand of cropping systems that generally decreases from south to north as rice based cropping systems are supplanted by wheat based cropping systems. The difference between the water demand of rice and wheat can easily be seen in Fig. 11 where higher IDs in the coastal zone are related to the triple rice cropping system while further north wheat supplants rice as the third (winter) crop in the south subtropical cropping zone.

In addition to this large-scale variations of ID variability at smaller scales becomes evident particularly in the L scenarios. The high-resolution climate data allow to distinguish features that are related to the varied topography of China such as rain augmenting mountain ranges or dry valleys and basins influenced by foehn winds. Most of the available climate data bases lack a corresponding resolution and fail to display this pattern of moist and dry areas that are an important feature of the agricultural landscape particularly of southern China.

The general ID pattern of the main crop is roughly identical to the mean soil moisture deficit given by Tao et al. (2003a) who however fail to identify the contribution of individual cropping systems. Their projected changes in soil moisture deficit for the years 2021–2030, based on data from the HADCM2 GCM, also roughly resemble the S2030 scenario. The low resolution of the GCM data resampled to a 0.5° grid however does not allow to decide if differences occur due to different climate projections or are the result of the low resolution.

Spatial interannual variability of the boundary of this region can in most cases be traced to intrannual variations of precipitation, particular to the onset and to some extent to the end of the rainy season. ID values given here assume that during all phenological stages of the crop ET_m has to be reached in order to obtain maximum yields. While insufficient soil moisture in the early stages of crop development cannot be overcome by sufficient soil moisture at later stages slight soil moisture deficits during the ripening stage are not detrimental or may even lead to higher yields (Doorenbos and Kassam, 1986). ID values given here therefore have to be regarded as upper limits that may fall considerably below these values without compromising yields. About 80–85% of observed yields can be explained by the yield index, the seasonal relation of ET_m to ET_a (Doorenbos and Kassam, 1986).

Spatial information on soil type and soil depth can be estimated from digital soil data bases such as in FAO (2000). When using soil data from different countries care has to be taken as in some cases homogenisation of soil information from different countries has not been entirely successful. Within China however soil induced variability clearly is of secondary importance compared to climatic variability. Several authors have stressed the importance of using exact soil data to estimate water balances (Frére and Popov, 1979; Feddema, 1998). In China 50–75% of annual precipitation is received in the main growing season so that during the rainy season most of the plant water demand is directly met by precipitation. Where either begin or end of the rainy season extends to a considerable part beyond the growing season and where monthly water availability is lower than the soil water storage capacity soil moisture capacity however may play an important role. In China three types of variability induced precipitation types and associated regions can be identified. In Southwest China the onset of the rainy season is highly variable (Thomas, 1993) but the total amount of precipitation over the growing season is in general sufficient for stable yields without excessive irrigation. South and Southeast China are generally classified as fully humid as the total amount of precipitation always meets crop water demands but high intraannual variability of individual months during the rainy season may inflict sporadic drought damage to crops. If only long-term monthly totals are considered no water deficit appears to occur over the growing season. The representation of intraannual variability in S2030 scenarios however allows to predict that IDs will increase sharply in dry years south of the Yangtze River basin. This is related to an observed increase in precipitation variability during individual monsoon months. Despite partially increasing precipitation totals over the entire rainy season crop water availability may be reduced as monthly precipitation totals vary considerably.

Northeast China and Inner Mongolia are located at the northern margins of the summer monsoon precipitation belt where the total amount of precipitation is in general barely sufficient to meet cropping needs. In this transitory region the northern extent of the monsoonal rain belt varies in response to the intensity of the monsoonal circulation. Due to high interannual variability a number of years with sufficient water availability can be observed. At the northern margin along the Huang He S2030 scenarios see an increase in ID that can be interpreted as a decrease of monsoonal activity and related rainfall fields. Signs of an altered circulation activity have been reported

by Gong and Ho (2003) and are signaled through decreasing PET rates that are linked to decreasing wind speeds (Thomas, 2000a; Chen et al., 2005, 2006; Wang et al., in press). Further to the northeast water availability in already drought stricken Northeastern China is predicted to be reduced even further which again may be related to an increased variability of the northern monsoon region boundary.

5. Conclusions

This study has shown that interannual climatic variability is a key factor in evaluating the effects of climate change on irrigation demand in China. In most studies (Chen et al., 1992; Hulme et al., 1992; Heilig et al., 2000; Tao et al., 2003b) climatic variability however has not or only marginally been accounted for. Both interannual and intrannual variability has to be represented in climate data in order to arrive at a realistic model of actual or future cropping conditions. Climate scenarios presented here give a statistical representation of the variability of potential future climates. Introducing observed variability into the scenarios can be seen as a sensitivity analysis of future cropping conditions that represent both long-term variability as well as extremes under the conditions of climate change.

The same applies to the required spatial resolution of input data and models. Highly variable spatial trend patterns not only of temperature and precipitation (Yatagai and Yasunari, 1994; Hulme et al., 1994; Böhner, 1996; Schäfer, 2001), but also of PET (Thomas, 2000a; Chen et al., 2005), sunshine duration, cloudiness, relative humidity (Kaiser, 2000) and air pressure (Böhner, 1996; Gong and Ho, 2003) have been found in China. Any meaningful climatic scenarios of future cropping conditions obviously cannot be based simply on mean values of temperature and precipitation taken from GCM results. Such an approach contradicts the observed spatial variability of trends that include regionally distributed positive and negative trends for all climatic variables.

The exact representation of the spatial and temporal distribution (timing and amount) of both precipitation and PET in a spatially distributed water balance model is crucial for realistic results. The large scale organisation of monsoonal precipitation events appears to be linked to small mountain ranges with altitudes of < 1000 m (Xie et al., 2006) requiring a resolution of < 60 km to map the spatial precipitation variability over China (Gao et al., 2006). Given the extent of morphological features such as the large river valleys that are important sites of agricultural production in China gridded climate data

with a spatial resolution of ≤ 25 km is required to represent the local climate. GCMs have not been able to offer an adequate resolution (Hulme et al., 1992; Beniston, 2003) but give rather coarse and general information in spatial terms. Advanced GCMs, coupled to a regional circulation model to give high-resolution output (e.g. Paeth et al., 2005) or downscaling methods with particular attention to topographic effects (e.g. Leung and Ghan, 1998) may solve the problem of insufficient spatial resolution of gridded climate data describing future climates.

The model presented here incorporates a dynamic response to interannual climatic variability by selecting an appropriate type of cropping system and begin and length of growing season according to climatic conditions. This is particularly important in China where multicropping has attained a multicropping index (total sown area/cultivated land in %) of >151% with grain production from multicropping totaling about 3/4 of the total grain output (Zheng, 1994). Multiple cropping systems account for about 50% of China's agricultural areas and are more sensitive to the timing and frequency of moisture and temperature conditions than average temperature or precipitation (Smit and Yunlong, 1996). Including the option to simulate multiple harvests with adequate climate controlled setting of cropping calendars should be regarded as mandatory for advanced agricultural models. Considerable attention has to be placed on this point as this study has shown that a mechanistically decision for a given cropping system based on a simple criterion is not a suitable tool for agricultural planning even at continental scales. State-of-the-art models such as the LPJ model (Gerten et al., 2004) will only make advances in our knowledge of cropping conditions if detailed regional cropping calendars and parameterization of local farming methods are added that match the detail of the model in general. The same applies to the already mentioned fact that the majority of the climatic input data available today have no adequate spatial resolution and suffer from several shortcomings exhibiting considerable deficiencies particularly in data that allow calculating PET.

In addition to climatic constraints a number of social, technical and economic aspects contribute to water problems in China. The preferences of individuals and communities in China for certain land use practices are partly shaped by economic incentives and interests, but are also guided by traditions and cultural interests (Jhaveri, 1994). In China paddy rice is grown in regions where climate and water supply would favour other crops such as corn, as is the case in the southwestern province of Yunnan. In these regions switching to crops with higher water use efficiency would already decrease the pressure on scarce water resources.

The adaptation to climatic change has always been a central aspect of Chinese farming systems (Smit and Yunlong, 1996) which will become even more pressing in many parts of China where drought is already a common problem nowadays. The climatic situation however is aggravated by irrational irrigation practices and management. Overuse of groundwater for irrigation in Northeast China has led to precariously dropping groundwater tables (Zhang et al., 2002) while Kharin et al. (1999) estimate that water losses in aging and poorly maintained irrigation networks may reach up to 80%. As irrigation water is in general still supplied free of charge the introduction of pricing mechanisms and institutional reforms are seen as mandatory to curb the waste of irrigation water (Yang et al., 2003).

Another option is to divert water from South China towards the north with the help of canals. Dating back to Imperial Chinese times the north–south water diversion project was again taken up several decades ago (Academia Sinica, 1980). Environmental problems of large scale water diversion combined with the social consequences of resettling entire villages and unsolved technical problems of lifting considerable amounts of water over intervening mountain ranges all contribute to a discussion about the rational of the plan (Liu, 1998). As only about 10% of the water supply of the project is earmarked for agricultural use a firm decision for this large scale water diversion project (Heilig et al., 2000; Tao et al., 2003b) based on arguments for an increased agricultural water supply appears unreasonable.

The most effective way however appears to be the reduction of PET by introducing water saving practices. A growing number of publications (Deng et al., 2000; Wang et al., 2000; Zhang et al., 2000; Barton et al., 2004; Belder et al., 2004; Wang et al., 2004; Debaekea and Aboudrareb, 2004; Huang et al., 2005; Mo et al., 2005; Qu et al., 2005) suggests that water saving practices ranging from mulching with straw or plastic to more efficient irrigation scheduling can save between 15–50% of irrigation water without decreasing yields. A regional study of Northeast China suggests that only a reduction of PET, either by reducing the irrigated or planted area, planting less water consuming crops or using water saving practices, would lead to sustainable water use (Kendy et al., 2003). Further spatial distributed studies at regional scales with appropriate high-resolution spatial climate and crop calendar data

would allow to quantify the effects of different options and identify possible solutions.

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