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# Hydrological responses to climate change and irrigation in the Aral Sea drainage basin

Yoshihiro Shibuo,[1] Jerker Jarsjö,[1] and Georgia Destouni[1]

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[1] Hydrological model interpretation of the water flow development in the Aral Sea Drainage Basin (ASDB) indicates that the water diversion and irrigation schemes in this region have considerably increased evapotranspiration and thereby decreased net water flux (precipitation minus evapotranspiration) from the atmosphere to the surface of the ASDB. Increased evapotranspiration cools the irrigated areas, and the decrease of net atmospheric water influx to the ASDB may also have non-local effects outside the basin. Such effects have previously been estimated by atmospheric modeling, assuming a global average evapotranspiration return flow to the atmosphere of about 40% of irrigation. Our results indicate larger return flows, of nearly 100% of the applied irrigation water in the ASDB, which may also imply considerably larger than previously estimated non-local water and climate effects of the world's irrigated areas.

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## 1. Introduction

[2] A series of recent studies have indicated that land surface irrigation may have important effects on surface temperature and vapor flux to the atmosphere by evapotranspiration (ET) [*Boucher et al.*, 2004; *Gordon et al.*, 2005; *Lobell et al.*, 2006; *Kueppers et al.*, 2007]. From a climate change perspective, these effects may bias our understanding of and mislead comparisons between climate model projections and surface observations of greenhouse warming. Increased ET may also have important implications for water resource management, by changing the regional water resource use and transferring water from the irrigated to other regions. Water management adaptation to climate and hydrological change may be misled if these ET effects are not properly understood.

[3] Large-scale irrigation and associated increased ET effects on surface temperature have so far been studied by atmospheric [*Boucher et al.*, 2004; *Lobell et al.*, 2006; *Kueppers et al.*, 2007] modeling with relatively low surface resolution and without consideration of the interconnections between ET and inland water fluxes through the water balances of drainage basins. These interconnections imply that large-scale atmospheric model results may actually be checked against runoff observations combined with independent hydrological model results of water balance-controlled water and vapor fluxes on drainage basin scales.

[4] A unique possibility for such basin-scale hydrological quantification and checking under conditions of both large irrigation and climatic change is provided by the dramatic water flow changes in the Aral Sea Drainage Basin (ASDB) and associated shrinkage of the Aral Sea. The Aral Sea shrinkage started soon after major water diversion and irrigation schemes commenced in the region about 1960. These schemes were intensive and numerous irrigation canals have been constructed. The largest, Karakum canal exports annually around 8–12 km$^3$ of water from the ASDB to other areas [*Glantz*, 2005]. Furrow irrigation has been, and still is, the predominant irrigation method within the ASDB [*Saiko and Zonn*, 2000]. The method implies that surface waters are spread over the agricultural fields, using open trenches separated by ridges that are often less than a meter wide. As a consequence of these diversions and the availability to evaporation of the diverted water, the river runoff into the Aral Sea decreased dramatically and was occasionally more or less zero in the 1980s.

[5] In addition to these water diversions, however, climate change manifestation in the ASDB since the 1960s may also have affected the hydrological cycling and the Aral Sea shrinkage. And to some degree, both the Aral Sea shrinkage itself [*Small et al.*, 2001] and the mega-irrigation schemes in the region [*Boucher et al.*, 2004; *Lobell et al.*, 2006; *Kueppers et al.*, 2007] may also have affected regional surface temperature and climate.

[6] The main aim of this study is to quantify the relative and combined effects of regional irrigation and climatic change on ET in the ASDB, as an integral part of the overall water balance of the basin. Actual ET is very difficult to measure directly and accurately over scales much larger than on the 1–10 m order of magnitude. Our understanding of regional to global ET is therefore generally dependent on modeling and subject to relatively large uncertainty. In the ASDB, however, ET change modeling may be possible with reasonable certainty because other main hydrological changes in this basin (precipitation and river discharge into and storage change in the Aral Sea) are large and essentially known, while more uncertain hydrological changes (in groundwater flow and storage) have recently been subject to detailed investigations and are relatively small [*Jarsjö and Destouni*, 2004; *Shibuo et al.*, 2006]. We here analyze ET and hydrological changes in the ASDB through three model scenarios, representing (1) a pre 1950's base condition, before the major influences of climate change and irrigation schemes, (2) a hypothetical scenario for the recent 1983–2002 period, considering climatic change effects only (neglecting the major irrigation schemes) and (3) a realistic

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[1] Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden.

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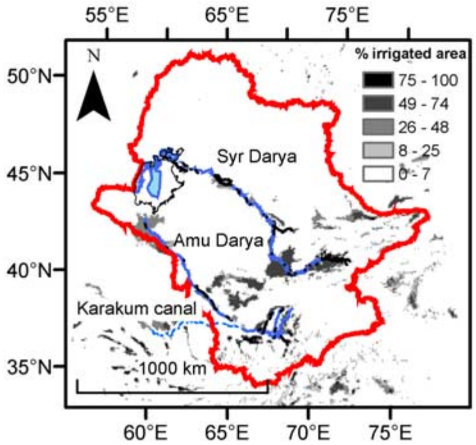

**Figure 1.** The Aral Sea Drainage Basin (ASDB; red line), with indicated extent of the Aral Sea in 2005 (filled blue) and before its major shrinkage (outlined with black line; Digital Chart of the World, available at http://www.maproom.psu.edu/dcw/, 1992), the Amu Darya and Syr Darya rivers (solid blue lines), main irrigated areas (grey scale, depending on irrigated area fraction [*Siebert et al.*, 2005]), and the constructed Karakum canal (dashed blue line), which dominates irrigation water exports from the ASDB, in addition to some water exports to minor irrigation area extensions outside the ASDB.

scenario for recent conditions, accounting for both climatic change effects and irrigation schemes.

## 2. ASDB Delineation and Hydrological Modeling

[7] Relatively widely applied PCRaster/Polflow model routines [*de Wit*, 2001; *Jarsjö et al.*, 2007; *Lindgren et al.*, 2007] were used for ASDB delineation (Figure 1), construction of the topography-controlled flow network, and calculation of the precipitation surplus (PS; precipitation minus evapotranspiration) in all 3000 × 3000 grid cells, as well as discharges (network-routed sum of PS from upstream areas). Given spatially distributed precipitation (P) and temperature (T) data for the whole ASDB, as independently reported in the Climate Research Unit (CRU) TS 2.1 data base [*Mitchell and Jones*, 2005], we used two methods for estimation of ET, in order to quantify the modeled ET sensitivity and uncertainty depending on the choice of ET model method. Different estimates $ET_{1a}$ and $ET_{th}$ of the potential $ET_p$ were obtained according to *Langbein* [1949] and *Thornthwaite* [1948], respectively. We considered the superficial nature of the ASDB irrigation water by adding its contribution as extra P over the irrigated fields. Actual evapotranspiration $ET_a$ was then estimated according to *Turc* [1954] as function of P and $ET_p$ from any of the two methods $ET_{1a}$ or $ET_{th}$. More details on the procedures are given in the auxiliary material[1] (see also *Shibuo* [2007] for a detailed discussion on the model approach and its applicability). Whereas our results regard changes occurring on land throughout the extensive ASDB, we refer to *Small et al.* [2001] and references therein for studies of corresponding changes over the considerably reduced open water volume of the Aral Sea itself.

[8] For model validation under pre-1950 conditions, resulting modeled Amu Darya and Syr Darya discharges are compared with observed river discharge data from two independent runoff data bases obtained from the Global Runoff Data Centre (Koblenz, Germany, available at http://grdc.bafg.de) and S. Mamatov (personal communication, 2004). For post-1950 conditions, the Global Map of Irrigated Areas [*Siebert et al.*, 2005] was used for identifying main irrigated areas within the ASDB (grey areas in Figure 1). The post-1950 river water diversions and inputs to these main irrigated areas were estimated from the difference between modeled river discharges at the Amu Darya and Syr Darya river mouths without irrigation and corresponding observed river discharges. The resulting discharge difference was for the Amu Darya and Syr Darya catchments uniformly distributed over the irrigation areas within each catchment, after accounting also for irrigation water exports from the ASDB.

## 3. Results

[9] The total delineated ASDB area (Figure 1) is 1,874,000 $km^2$, of which the individual Amu Darya and Syr Darya catchments constitute a major part, and smaller unmonitored catchment areas (most in the north, around the Small Aral) amount to a total area of about 321,000 $km^2$. The left panels in Figure 2 summarize the 20th century trends of reported area-averaged (over the whole ASDB) T and P observation data. The 20-year running T average exhibits a steady increase since 1950, i.e., since just before the start of the dramatic Aral Sea shrinkage. Also the post-1950 average P is somewhat larger than the pre-1950 average P.

[10] The right panels in Figure 2 illustrate further the spatial distributions of reported T and P changes in the ASDB. From pre-1950 to recent conditions, T increased mostly in the northwestern part of the basin, while P decreased in this part and increased in the southeastern irrigated areas and adjacent mountainous areas. In the following, we use the independently reported spatial-temporal developments of T and P since the 1950s, in conjunction with available information about the major irrigation schemes and the Aral Sea shrinkage, which also started around that period, in hydrological modeling of the ASDB for three different model scenarios with ET as the main unknown.

[11] The first, scenario 1, is a base, pre-1950 temporal (1901–1950) average scenario, representing the relatively undisturbed (called here, for simplicity, natural) hydrological conditions before the major influences of climate change and irrigation schemes. Temporal average T and P values for the period 1901–1950 are considered as representative boundary conditions for scenario 1. It is further assumed that irrigation activities before 1950 were localized and so small relative to precipitation that they may be neglected. Table 1 summarizes average T and total P values for the whole ASDB along with the independently modeled river and other discharges into the Aral Sea and associated total ET for scenario 1.

[12] The independently modeled river discharges are more or less similar to observed discharges for both

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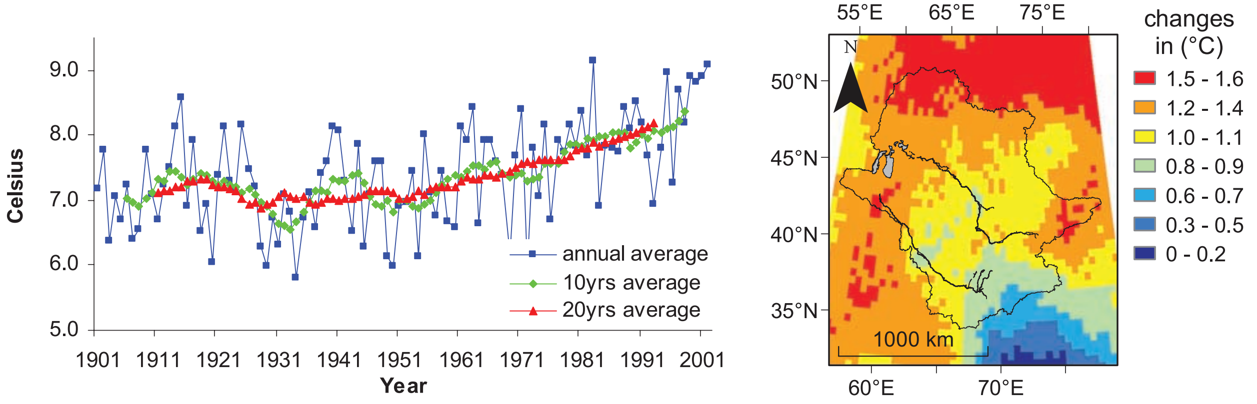
[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL031465.

a) Temperature



b) Precipitation

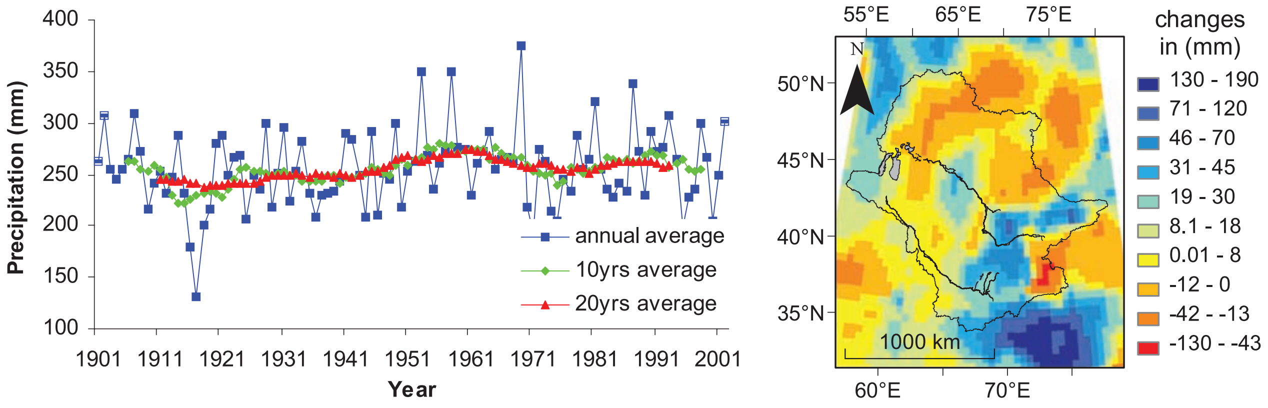


**Figure 2.** (a) Temperature and (b) precipitation data within the ASDB [*Mitchell and Jones*, 2005]. (left) Temporal trends. (right) The spatial distribution of change between the temporal (50 years) average pre-1950 condition and the recent 20 years (1983–2002) average condition.

**Table 1.** Summary of Temperature and Water Flows in the ASDB for the Three Different Investigation Scenarios[a]

| | | Scenario 1: 1901–1950, Natural | | Scenario 2: 1983–2002, Climate | | Scenario 3: 1983–2002, Climate-Irrigation | |
|---|---|---|---|---|---|---|---|
| | | ETla | ETth | ETla | ETth | ETla | ETth |
| Average temperature (°C) | | 8 | | 9 | | 9 | |
| Total precipitation (km3/yr) | | 467 | | 487 | | 487 | |
| Internal water redistribution to irrigation (km3/yr) | | 0 | | 0 | | 50 | 37 |
| Water export (km3/yr) from the ASDB through: | Karakum canal | 0 | | 0 | | 12 | |
| | Other irrigation transfer | 0 | | 0 | | 2 | 2 |
| Total modelled ET flux (km3/yr) | | 391 | 410 | 409 | 426 | 458 | 463 |
| Mean reported discharges into the Aral Sea (km3/yr) from | Amu Darya | 48 | | | | 8 | |
| | Syr Darya | 23 | | n.a. | n.a. | 4 | |
| | Total | 71 | | n.a. | | 12 | |
| Modeled discharges into the Aral Sea (km3/yr) from | Amu Darya | 43 | 37 | 44 | 39 | 8 | 7 |
| | Syr Darya | 30 | 20 | 31 | 23 | 5 | 4 |
| | Unmonitored | 4 | 0 | 3 | 0 | 3 | 0 |
| | Total | 77 | 58 | 78 | 62 | 16 | 11 |

[a] Columns ETla and ETth refer to model results based on the two different ET calculation methods explained in the main text and auxiliary material. For the estimated water export through the Karakum canal (dashed blue line in Figure 1), the maximum value within the reported range [*Glantz*, 2005] is used in order not to overestimate the modeled ET flux.

evapotranspiration models $ET_{la}$ and $ET_{th}$, and the model estimates of unmonitored (small stream and groundwater) contributions to the Aral Sea are consistent with previous estimates of pre-1950 conditions in the Aral Sea region [*Jarsjö and Destouni*, 2004; *Shibuo et al.*, 2006]. These consistencies give some confidence in the modeled total ET for the ASDB, which is also consistent between the two ET models (less than 2.5% difference from their mid-range value). In order to estimate climate and irrigation effects on this total ET flux, we simulate further two other scenarios for average recent conditions (1983–2002) and compare their hydrological cycling implications relative to the natural base scenario 1.

[13] The second investigation scenario 2 (referred to as the climate scenario) is a purely hypothetical scenario, assumed to represent the possible recent 20-year (1983–2002) conditions that might have prevailed in the ASDB if only climatic change had occurred, without any water diversions, irrigation schemes and associated effects occurring at the same time. Observed P and T data, averaged over the 1983–2002 period are used here as drivers for the hydrologic modeling. The main questions of this scenario investigation are: To what degree may the regional climatic (T and P) changes alone (i.e., without any irrigation changes) explain the river discharge changes from pre-1950 (scenario 1) to present conditions? And what ET flux changes and feedbacks from the ASDB to the atmosphere might such climatic changes alone lead to?

[14] The indicated answers from the hydrological ASDB modeling are listed in the scenario 2 results of Table 1. The regional T and P changes do not at all explain the river discharge decrease in the ASDB; if anything, the climatic changes alone lead rather to a 6% increase of river discharges, from about 66 $km^3$/year (midrange value in ±15% ET method range) to about 70 $km^3$/year (midrange value in ±11% ET method range), which is rather insignificant in relation to and masked by the large river discharge decreases implied by the engineered water diversions. Furthermore, the about 1°C average temperature change in the ASDB appears to yield a total ET flux increase of about 17 $km^3$/year (4% change), from a pre-1950 value of about 400 $km^3$/year (midrange value in ±2.5% range) to a present value of about 417 $km^3$/year (midrange value in ±2% range). This 4% ET flux increase from the ASDB to the atmosphere balances nearly fully the about 20 $km^3$/year (4%) precipitation increase into the ASBD.

[15] The full post-1950 changes in the ASDB hydrology are investigated by model scenario 3 (referred to as the climate-irrigation scenario), which is assumed to be a realistic scenario for recent (1983–2002) conditions, accounting for both the regional climate change and the major irrigation schemes. The main question that this investigation scenario may answer is: What additional ET flux change does the irrigation lead to? Model results summarized in Table 1 show that the combined climate-irrigation scenario 3 yields an ET flux increase of about 43 $km^3$/year (about 10% change) relative to the pure climate scenario 2, and 60 $km^3$/year (15% change) relative to the natural base scenario 1. This ET increase is larger than the P increase. Therefore, the total basin-scale net water flux (P minus ET) decreased by 60%, from about 66 $km^3$/year to about 26 $km^3$/year (Table 1). Note that the basin-scale P-ET in scenario 3 does not equal the total discharge from the basin to the Aral Sea, because the latter is also affected by the large irrigation water export from the ASDB to other basins. If the ET return flow from irrigation water inputs or/and the irrigation water inputs themselves were much smaller than modeled here, closure of the present-day ASDB water balance would

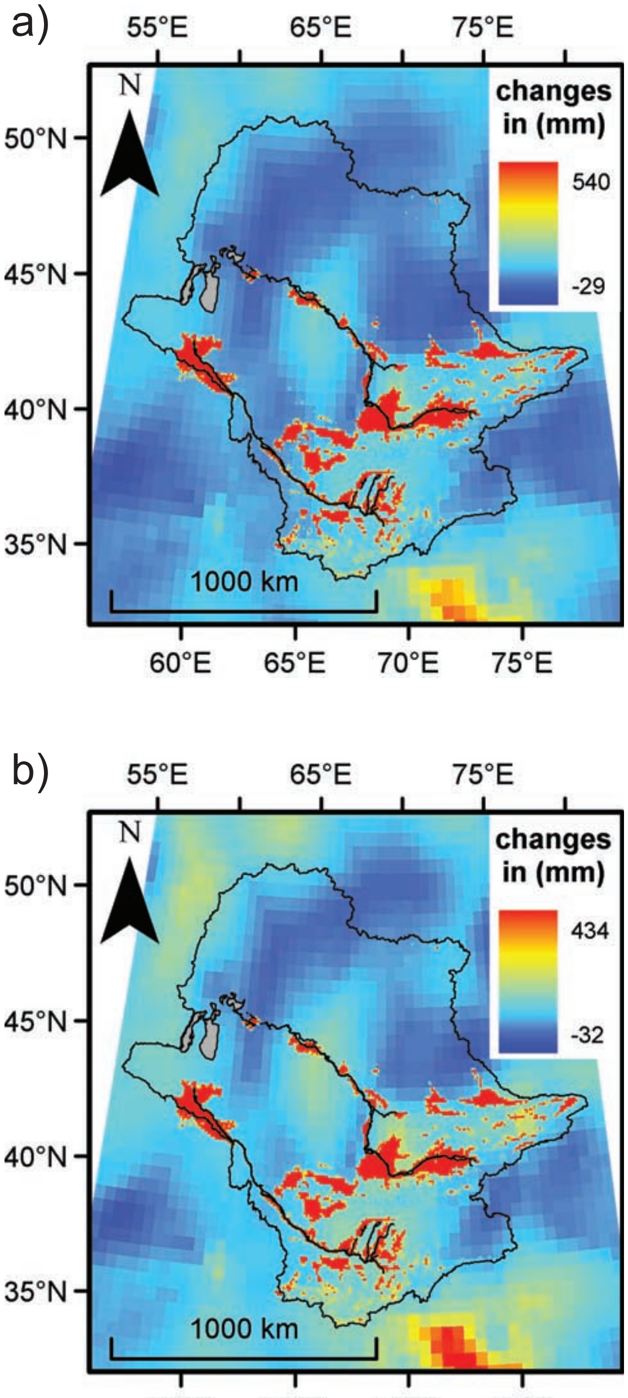


**Figure 3.** Evapotranspiration change in the climate-irrigation scenario 3 relative to the pre-1950 natural scenario 1, based on the two different ET calculation methods explained in the main text and auxiliary material: (a) ETla and (b) ETth.

require additional surface or groundwater flows into the Aral Sea or to other basins, which must be independently observable but have, to our best knowledge, so far not been reported in openly available literature or databases.

[16] Figure 3 shows the spatial distribution of the modeled ET increase from the natural scenario 1 to the climate-irrigation scenario 3. The ET increase occurs primarily over the main irrigation areas in the southeastern part of the ASDB, where also precipitation is reported to have increased, while temperature is reported to have increased much less than in the northwestern part of the basin (Figure 2).

## 4. Conclusions

[17] Our results indicate important effects of freshwater diversions and irrigation on regional water resources and climate. The excessive irrigation in primarily the southeastern part of the ASDB appears to have considerably increased ET and cooled this area in the process. By contrast, temperature increases are considerable in other (largely non-irrigated) areas of the ASDB, where hydro-climatic changes should reflect local effects of the Aral Sea shrinkage itself [*Small et al.*, 2001] in addition to the regional manifestation of global climate change. The main reported precipitation increase in the ASDB is also localized to the southeastern part and may also largely be an effect of the local ET increase due to irrigation; such influences of local land use changes on local climate have been found in other studies [*Douglas et al.*, 2006].

[18] Most of the modeled ET increase in the ASDB, however, must flow out from the basin in order to honor the basin's independently reported water balance terms. The increased vapor flux by ET from the ASDB may then in the atmosphere be transported to and affect water resources and local climate in other regions, and/or to higher altitudes adding to global radiative forcing. Even though the here quantified vapor flux changes over the ASDB may differ from the changes over the Aral Sea itself (which by definition is not a part of the ASDB), cancellation of any opposing trends is unlikely due the vast extent of the ASDB (1.8 million km$^2$) in relation to the much smaller Aral Sea extent (currently about 17,000 km$^2$). *Boucher et al.* [2004] has modeled non-local climatic effects of increased ET from the world's irrigated areas, by simply assuming an ET return flow to the atmosphere of about 40% (or 1006 km$^3$/year) of the total global irrigation water withdrawal (2353 km$^3$/year) reported by other studies [*Seckler et al.*, 1998; *Döll and Siebert*, 2002]. Hydrological studies (Shiklomanov and Markova [1987] as quoted by *Milly and Dunne* [1994]; *Gordon et al.* [2005]), however, have reported possible much larger (a factor 2.0) absolute global ET return flow from irrigation (2050 km$^3$/year) than that assumed by *Boucher et al.* [2004]; these hydrological global ET return flow estimates are more or less equal to the reported global irrigation water withdrawals [*Seckler et al.*, 1998; *Döll and Siebert*, 2002].

[19] The present regional ET model results, which honor and are backed up by the ASDB water balance and its independently reported flow components other than ET, provide support for the larger, hydrologically based global ET estimates, by indicating a return flow of 96% or more from the applied irrigation water. This implies possible considerably larger than previously estimated non-local water and climate effects of the world's irrigated areas, which should be investigated further in forthcoming research.

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G. Destouni, J. Jarsjö, and Y. Shibuo, Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106-91 Stockholm, Sweden. (georgia.destouni@natgeo.su.se)