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Hydrologic effects of land and water management in North America and Asia: 1700–1992

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Abstract

The hydrologic effects of land use changes, dams, and irrigation in North America and Asia over the past 300 years are studied using a macroscale hydrologic model. The simulation results indicate that the expansion of croplands over the last three centuries has resulted in 2.5 and 6 percent increases in annual runoff volumes for North America and Asia, respectively, and that these increases in runoff to some extent have been compensated by increased evapotranspiration caused by irrigation practices. Averaged over the year and the continental scale, the accumulated anthropogenic impacts on surface water fluxes are hence relatively minor. However, for some regions within the continents human activities have altered hydrologic regimes profoundly. Reservoir operations and irrigation practices in the western part of USA and Mexico have resulted in a 25 percent decrease in streamflow in June, and a 9 percent decrease in annual runoff volumes reaching the Pacific Ocean. In the area in South East Asia draining to the Pacific Ocean, land use changes have caused an increase in runoff volumes throughout the year, and the average annual increase in runoff is 12 percent.

1 Introduction

In ancient times some dams and aqueducts were built for irrigation and water supply, but the impact of human activities on streamflow was minor. More recently, water management structures have become increasingly essential to provide water supply, as well as electric power, navigation, flood control, and other amenities for a growing population. Dams, built for water storage, and water withdrawals, e.g. for irrigation purposes, directly change the dynamics of the water cycle, and humanity has extensively altered river systems through diversions and impoundments. In addition, surface water fluxes are indirectly influenced by land use changes, e.g. deforestation. Anthropogenic impacts have altered the natural water balance profoundly, at least at the local scale. Several rivers, like the Colorado, the Indus, and the Huang He Rivers are used so ex-

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tensively that during parts of the year little or no water reaches the sea (Falkenmark and Lannerstad, 2005), and the Aral and Caspian Seas have been reduced in extent because of water extractions for agriculture (Vörösmarty and Sahagian, 2000).

According to Vitousek et al. (1997), humans have transformed more than one-third of the Earth's land surface, mainly for the purpose of producing goods and services. The expansion of croplands has resulted in a 20 percent reduction in forest cover since 1700 (Ramankutty and Foley, 1999). Both field experiments and modeling studies have shown that reduced forest cover in general increases streamflow and reduces evapotranspiration (Sahin and Hall, 1996; Matheussen et al., 2000; Costa et al., 2003; Twine et al., 2004). According to FAOSTAT (available at http://faostat.fao.org/), a database maintained by the Food and Agriculture Organization of the United Nations (FAO), 2.8×10^6 km^2 land is currently (2003) equipped for irrigation globally; about twice the size of the area equipped for irrigation in 1961. Several modeling projects have studied the effects of irrigation on water balance components globally, e.g. Döll and Siebert (2002). Land use changes affect albedo and evapotranspiration, and the effects on climate have received much attention, both on the local and the global scale, see Gibbard et al. (2005), Lobell et al. (2006), and references therein, but continental-scale hydrologic analyses of the effect of land use changes are rare. Gordon et al. (2005) quantified changes in evapotranspiration due to deforestation and irrigation at the global scale, and concluded that the effects of irrigation on evapotranspiration are as important as the effects of deforestation.

In addition to land cover changes, humans have altered natural water cycles by building dams, and the World Register of Large Dams (ICOLD, 2003) includes more than 33 000 dams (defined as being 15 m or higher). The volume of water that can be stored in reservoirs formed by large dams is about 6600 km^3, or about 15 percent of annual continental runoff (Postel et al., 1996). The effects of dams on the water balance can be profound, see e.g. Vörösmarty et al. (1997), Nilssson et al. (2005), and Hanasaki et al. (2006). Haddeland et al. (2006b) studied the effects of dams and irrigation given current conditions, and found locally significant changes in the surface water fluxes.

The purpose of this paper is to study the hydrologic effects of dams in comparison with cropland expansion, and irrigation practices over the past 300 years for North America and Asia. 80 percent of the area equipped for irrigation globally (Siebert et al., 2005), and more than 70 percent of the world's large dams (ICOLD, 2003) are located within these two continents.

2 Approach

2.1 Hydrology model

The Variable Infiltration Capacity (VIC) macroscale hydrology model (Liang et al., 1994) is a grid-based model that usually is implemented at spatial scales from one-eighth to two degrees latitude by longitude, and at hourly to daily temporal resolution. Each grid cell is partitioned into multiple vegetation types, and the soil column is divided into multiple (typically three) soil layers. Evapotranspiration is calculated using the Penman-Monteith equation. The saturation excess mechanism, which produces surface runoff, is parameterized through the Xinanjiang variable infiltration curve (Zhao et al., 1980). Release of baseflow from the lowest soil layer is controlled through the non-linear Arno recession curve (Todini, 1996). Surface runoff and baseflow for each cell are routed to the basin outlet through a channel network as described by Lohmann et al. (1998).

An irrigation scheme and a reservoir model were recently added to the VIC model (Haddeland et al., 2006a, b). The irrigation scheme extracts surface water locally, or, in periods of water scarcity, from reservoirs or any other prescribed point in the river basin. The VIC model, like most land surface schemes, does not represent groundwater in a way suitable for modeling groundwater withdrawals, which hence is not taken into account in the model. Reservoir operations are based on information that can be found in the World Register of Dams (ICOLD, 2003), and georeferencing of the dams is obtained from Vörösmarty et al. (1997, 2003). The reservoir model and irrigation scheme are described in more detail in Haddeland et al. (2006a, b).

2.2 Study areas and input data

The regions studied include most of Asia (including parts of Eastern Europe), and North America (Mexico, USA, and Canada), see Fig. 1. These regions include some of the most heavily irrigated areas in the world, and account for about 80 percent of the areas equipped for irrigation globally (Siebert et al., 2005). In addition, about 70 percent of the dams registered in the World Register of Dams (ICOLD, 2003) are located in North America and Asia. Current land cover data (topography, vegetation, soil) and meteorological data are the same as described in Haddeland et al. (2006b). Potential vegetation (the vegetation that would have existed absent anthropogenic effects, and absent certain disturbances like fires and pests) and data on historical cropland cover were obtained from the SAGE database (available at http://www.sage.wisc.edu). These datasets are described in Ramankutty and Foley (1999), and include potential vegetation at 5 min resolution, and cropland data (fraction within cell) at 0.5 degrees resolution for the period 1700–1992.

Data on irrigated areas were obtained from Siebert et al. (2005), see Fig. 1. Information on areas equipped for irrigation within each country from 1961 up to now was obtained from FAOSTAT (available at http://faostat.fao.org/), see Fig. 2. The dam dataset used in this study globally includes 668 dams, of which 183 (total storage capacity: 1192 km^3) are located in the North American region, and 257 (total storage capacity: 1782 km^3) in the Asian region. Figure 3 shows the number of dams built within each 10-year interval since 1900, and the accumulated storage capacity of the dams.

3 Model analyses

3.1 Vegetation scenarios

In order to study the changes in streamflow associated with land-cover changes, several vegetation images were constructed, representing the current (~1992) and historical (1700, 1900, and 1950) conditions. The vegetation images were inferred from the current vegetation image, and Ramankutty and Foley's (1999) potential vegetation and cropland datasets.

In Haddeland et al. (2006b), vegetation types were obtained from Hansen et al. (2000) combined with leaf area index (LAI) values based on Myneni et al. (1997), as described in Nijssen et al. (2001). The cropland dataset (Ramankutty and Foley, 1999) includes larger areas of cropland in 1992 than Hansen et al.'s (2000) vegetation image. In order to make the comparisons between the current and historical simulations more consistent, the current vegetation image was slightly modified. That is, cropland areas in the current vegetation image were matched to the cropland areas of Ramankutty and Foley (1999). The modified current vegetation image thus has more cropland areas than the original vegetation image; mainly on the expense of wooded grasslands and grasslands. If Ramankutty and Foley's (1999) cropland dataset had cropland in a cell where the current vegetation image contains no cropland, LAI values for cropland were taken from adjacent cells and averaged. The original and modified vegetation images are shown in Fig. 4.

Ramankutty and Foley's (1999) potential vegetation image is available at 5 min (1/12 degree) spatial resolution. These data were aggregated to 0.5 degrees spatial resolution, where each resulting grid cell includes information on fraction of each vegetation type within the area covered by the 0.5 degree grid cell. Ramankutty and Foley (1999) classifies vegetation somewhat differently than does Hansen et al. (2000), and the potential vegetation images was therefore matched to Hansen et al.'s (2000) classification scheme. LAI values for the potential vegetation were thereafter inferred from the current vegetation image.

Historical (1700–1950) vegetation images were constructed by adjusting cropland area in the modified current vegetation image according to Ramankutty and Foley's (1999) information on changes in cropland fraction within each 0.5 degree cell between 1992 and the year of interest. Cropland areas were substituted with potential vegetation, or, in the case of a higher historical than current percentage cropland within the cell, current vegetation types were replaced by cropland. Table 1 gives the amount of different vegetation types in the current and historical vegetation images, see also Fig. 4.

3.2 Irrigated areas

The global map of irrigated areas from Siebert et al. (2005) was used as the baseline image of irrigated areas around the year 2000. FAOSTAT (available at http://faostat.fao.org) includes information on irrigated areas in each country for each year since 1961, see Fig. 2. For countries that were former a part of USSR, USSR information for the period 1961–1990 were used to estimate the change in irrigated areas within each country. For all countries, estimates for 1950 were obtained by extrapolating the data for the period 1961–1970 (assuming a linear trend). No irrigation was included in the simulations for 1900 and before. The location of irrigated areas were somewhat adjusted, to make sure fraction irrigated area within each cell is less than, or equal to, cropland area given by Ramankutty and Foley (1999). However, changes in irrigated area within each country for each year were constrained to the FAOSTAT values.

3.3 Model simulations

Model simulations were performed for current (~1992) and historical (1700, 1900, and 1950) conditions. For 1950 and 1992, simulations were performed both with and without the irrigation scheme and reservoir module implemented, which allows study of land use changes alone. For the simulations with the reservoir model included, only dams that were built within the simulation year were taken into account. For all simulations, the same meteorological input data were used. Hence, the results should be interpreted as indicating the predicted hydrologic response where the indicated land cover and water management scenarios to occur with the current climate (stated otherwise, the effects of possible climate change over the past 300 years is not considered).

4 Results and discussion

Figure 5 shows simulated mean annual evapotranspiration values within each 0.5 degree grid cell for current conditions, both with and without the reservoir and irrigation scheme implemented, compared to the historical (1700) values. Areas where current evapotranspiration values are different from the historical values to some extent reflect the vegetation changes shown in Fig. 4. Conversion of land area from forest or woodland to cropland leads to decreased evapotranspiration and increased runoff, e.g. in Florida, in Russia north of ~50 N, and in Eastern and South East Asia, see Fig. 5a). In these areas current LAI values are lower than historical LAI values (see Fig. 4), which in general leads to increased runoff (Sahin and Hall, 1996). In Russia south of ~50N, which originally was dominated by grassland but is currently dominated by cropland, the opposite trend is apparent, and current evapotranspiration values are higher than historical evapotranspiration values. When looking at Fig. 5c), it is apparent that the areas that are relatively most affected by irrigation practices are located in the USA, Pakistan, India, and China.

In the Mississippi River basin, simulated evapotranspiration has decreased in the eastern part, which has been converted from forested areas to cropland, and increased in the western part, which has experienced conversion from grassland to cropland, see Fig. 5. Twine et al. (2004) studied the effects of land cover changes on the water balance of the Mississippi River basin, and found 10 percent decreases in mean annual evapotranspiration values over areas of former forest and savanna, and 15 percent increase in mean annual evapotranspiration values over areas of former grasslands. In general, these trends are similar to the ones seen in Fig. 5a), which compares the historical situation to the current situation, without taking reservoirs and irrigation practices into account.

Total simulated current runoff values for the North American and Asian regions are 6050 and 15 500 km^3 year^{-1}, respectively, while the corresponding numbers on evapotranspiration are 9600 and 23 200 km^3 year^{-1}. Water balance numbers for all simulations are presented in Fig. 6. The simulations are performed using the same 20-year period (1980–1999) of meteorological data, i.e. the simulation results are not affected by possible climate changes. Figure 6 indicates that land use changes in the Asian region on average have affected runoff and evapotranspiration more than in the North American region. The largest simulated increases in runoff values are about 3 percent for North America, and about 6 percent for Asia. In Asia, the highest simulated total runoff is for current conditions without taking reservoirs and irrigation practices into account, and land use changes have caused a gradual increase in runoff over the past 300 years. Simulated irrigation water requirements in Asia are about 70 percent of the simulated decrease in evapotranspiration caused by land use changes, whereas simulated water use is about half this number. In North America, cropland mainly replaced areas of forest and woodland between 1700 and 1900, resulting in an increase in runoff values. Between 1900 and 1950, the agricultural expansion in the Midwestern USA took place on the expense of grassland areas (see also Fig. 4), and runoff consequently decreased somewhat in these areas compared to the 1900 values. Elsewhere, e.g. in Florida, cropland areas replaced forested areas during the same 50-year period, and averaged over North America runoff increased between 1900 and 1950. After 1950, cropland expansion results in decreased runoff values. Simulated irrigation water requirements in North America are higher than the simulated increases in runoff values caused by land use changes. However, simulated current water uses are similar to the simulated increases in runoff values caused by land use changes, and simulated current runoff and evapotranspiration are hence practically the same as the 1700 values.

Gordon et al. (2005) found that deforestation has decreased global vapor flows by

3000 km^3 $year^{-1}$, and that global irrigation water requirements are 2600 km^3 $year^{-1}$, but they do not report results by continent. It is, however, evident that the Gordon et al. (2005) numbers for North America and Asia are higher than the simulations presented here. The irrigation water requirements presented in Fig. 6 are in reasonable agreement with the irrigation water requirements reported in FAO's database AQUASTAT (http://www.fao.org/ag/agl/aglw/aquastat/main), see also Haddeland et al. (2006b). The Gordon et al. study (2005) reports substantial decreases in evapotranspiration caused by land use changes in Eastern China, decreases that are not as significant in this study. Differences in the vegetation images and models are most likely the main factors that lead to the discrepancies. The LAI values used for 1700 conditions (see Fig. 4b), and method of calculating evapotranspiration in this study, might result in less evapotranspiration than the method used by Gordon et al. (2005).

Simulated mean monthly runoff for various continental areas to the ocean is shown in Fig. 7, which in addition shows runoff relationships between the simulation results. At the monthly level, the largest simulated differences between current (~1992, reservoirs and irrigation included) and historical (1700) conditions are observed in the early summer in the North American area draining to the Eastern Pacific south of 49 N (i.e. the western part of USA and Mexico), and in the winter in the areas draining to the West Atlantic, and the Arctic Ocean. In 1950, the largest changes from the 1700 conditions are in the area draining to the Eastern Pacific south of 49 N. The increasing number of dams and extent of irrigated areas in the 1900's in North America are obvious when looking at the graphs for 1900, 1950, and 1992. Figure 7 also indicates that the main impact of dams in Asia occurred after 1950, see also Fig. 1.

The effects of land use changes (i.e. the difference between simulations 1 and 4 in Fig. 7) are most noticeable in the North American area draining to the Gulf of Mexico, and the Asian areas draining to the Pacific Ocean. These areas all experiences higher current than historical runoff, given no irrigation and no reservoirs. Figure 7i) indicates that reservoir and irrigation practices decreases runoff by about the same amount as decreased forest cover increases runoff in this area, whereas irrigation water use in

South East Asia (Fig. 7h) does not balance the increase in runoff caused by decreased forest cover, see also Fig. 6.

Figure 8 shows accumulated volume of freshwater reaching the oceans, and indicates that the area in North America draining to the Gulf of Mexico, and the area in South East Asia draining to the Western Pacific Ocean, are the two areas where annual runoff volumes have been most affected by land use changes, at least in a relative sense. For the area draining to the Gulf of Mexico, the simulation results for 1992 without the reservoir and irrigation model implemented, indicates an increase in runoff of 9 percent, compared to the simulation results for 1700. However, because of irrigation water use, the current simulated runoff with the reservoir and irrigation scheme implemented is only 3.5 percent higher than the 1700 results. In South East Asia (the area draining to the Pacific Ocean), the corresponding numbers are 12 and 11 percent.

The results presented here are dependent on the quality of the current and historical vegetation images, and the method chosen when constructing these images will influence the results. It should also be kept in mind that the land use changes taken into account in this study only include areas converted to cropland. As pointed out by Ramankutty and Foley (1999), other forms of land use changes can have important hydrological consequences. Also, the potential vegetation does not necessarily represent the natural pre-agricultural vegetation, but instead represent vegetation that likely would exist today given no human activities or other disturbances, like fire (Ramankutty and Foley, 1999).

Simulated irrigation water use is most likely somewhat underestimated, given that groundwater withdrawals are not included in the modeling scheme, see discussion in Haddeland et al. (2006a, b). Also, for the 1950 and 1992 simulations, the same vegetation image is used for the simulation where irrigation is taken into account, and the simulation without irrigation. Wilting of plants is not taken into account in the model, which might have affected leaf are index somewhat in the simulations where irrigation is not taken into account. Both these factors would most likely have increased the difference between the two simulations performed for 1950 and 1992.

5 Conclusions

Simulation results indicate an increase in annual runoff between 1700 and 1992 caused by cropland expansions in North America and Asia of 2.5 and 6 percent, respectively. The runoff increases are caused by conversion of forest and woodland to cropland. In North America the agricultural expansion in the 20th century has replaced large grassland areas, resulting in slightly lower runoff in 1992 than in 1950, considering the effect of land use changes alone. Irrigation increases evapotranspiration and decreases runoff, and in North America irrigation water use to some extent cancels out the simulated increase in runoff caused by land use changes over the past 300 years. In the Asian region, simulated irrigation water requirements for current conditions are slightly lower than the simulated increase in runoff caused by land use changes. However, simulated irrigation water use is only about half the amount of irrigation water requirements.

The areas draining to the Arctic Ocean are, on average, insignificantly affected by land use changes and irrigation. However, dam construction has altered the streamflow regimes somewhat in these areas, especially in March when simulated current streamflow is between 20 and 40 percent higher than simulated historical streamflow for the northern part of North America and Asia. On the basis of the total impact of land use changes, irrigation, and dams, the relatively largest changes in annual runoff volumes are simulated in the South East Asian area draining to the Pacific Ocean, where simulated current annual runoff volumes are 11 percent lower than the simulated historical runoff volumes. The largest changes caused by land use changes alone are also simulated in the South East Asian area, where current simulated annual runoff is 12 percent higher than historical simulated runoff. Irrigation practices decreases annual runoff volumes the most in the area draining the western part of USA and Mexico, where current simulated annual runoff volume with the irrigation and reservoir model implemented is 9 percent lower than current simulated annual runoff volume without the irrigation and reservoir model implemented. For the same area, the maximum monthly decrease in streamflow is 25 percent, and is caused by reservoir operations combined with irrigation practices.

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Table 1. Vegetation cover in study area (10^6 km^2), 1700–1992.

	1700	1900	1950	1992
Forest	16.1	13.1	12.1	11.2
Woodland (includes wooded grassland)	17.9	16.5	15.8	15.8
Shrubland	15.5	15.2	14.9	14.6
Grassland	10.1	8.4	7.5	7.1
Bare soil	2.8	2.8	2.8	2.8
Cropland (irrigated)	2.4 (0)	8.4 (0)	11.2 (0.9)	12.6 (2.1)
Total	69.4	69.4	69.4	69.4

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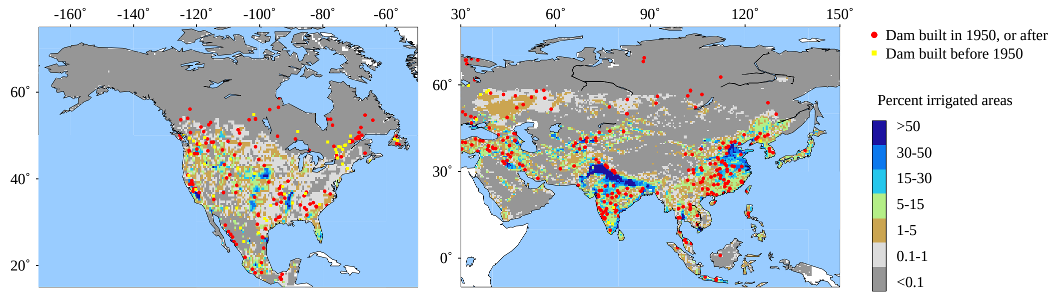

Fig. 1. The study areas, including the location of the dams taken into account in this study, and the percent irrigated area within each 0.5 degree grid cell.

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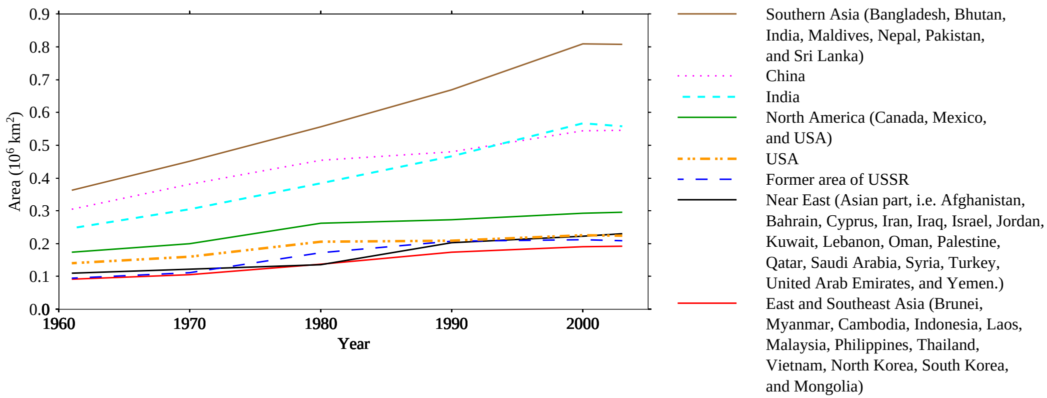

Fig. 2. Irrigated areas, 1961–2003.

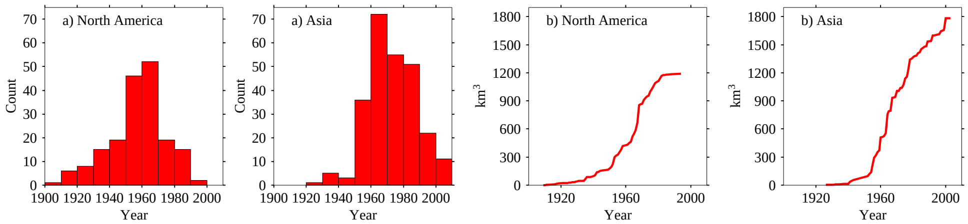

Fig. 3. (a) Histogram of when the dams were built, and **(b)** Accumulated storage volume. Only dams included in this study are taken into account.

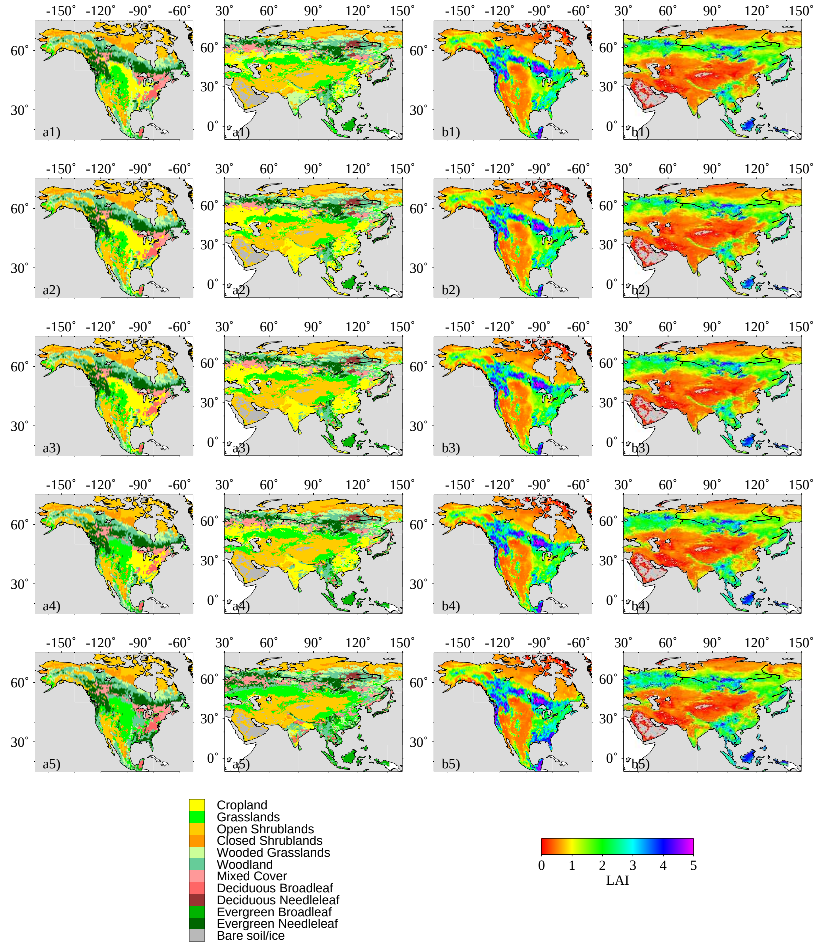

Fig. 4. **(a)** Dominant vegetation type, and **(b)** mean annual leaf area index value within grid cell.1: 1992 (original), 2: 1992 (modified), 3: 1950, 4: 1900, 5: 1700.

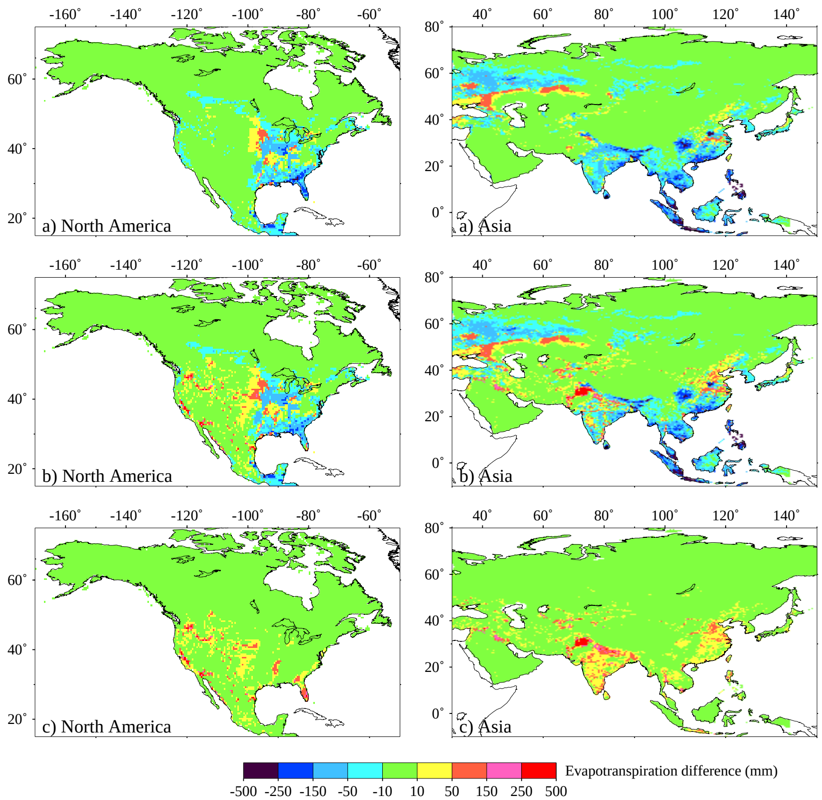

Fig. 5. Spatial effects on evapotranspiration. **(a)** The difference between current (1992) simulation results, without irrigation and reservoirs, compared to historical (1700) simulation results. **(b)** The difference between current (1992) simulation results, with irrigation and reservoirs, compared to historical (1700) simulation results. **(c)** The difference between current (1992) simulation results, with irrigation and reservoirs, and current (1992) simulation results, without irrigation and reservoirs. Notice the uneven legend intervals.

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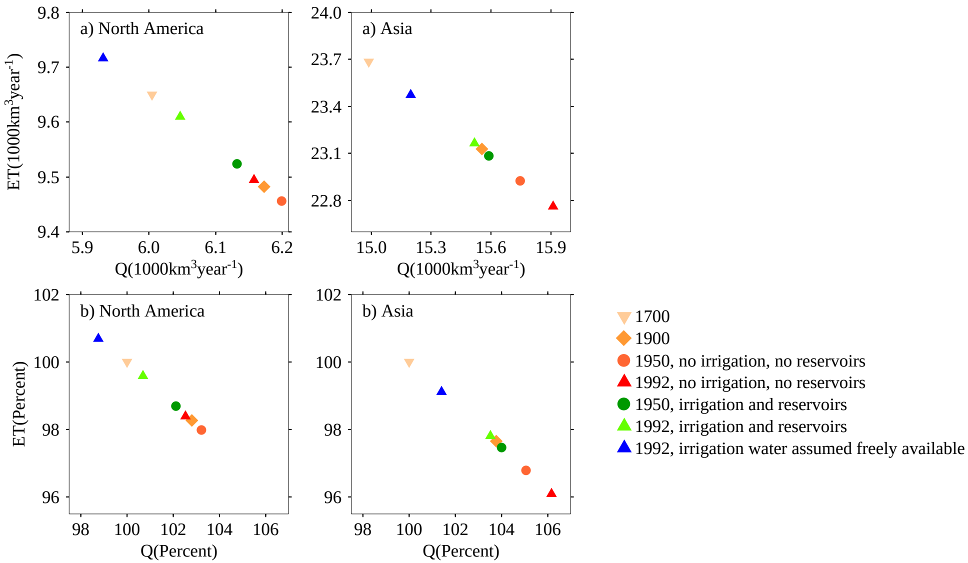

Fig. 6. Water balance components (ET: Evapotranspiration, Q: Runoff) for all simulations. **(a)** Mean annual values, and **(b)** Relative amount compared to the simulations for the year 1700. The numbers do not include reservoir evaporation or changes in reservoir storage.

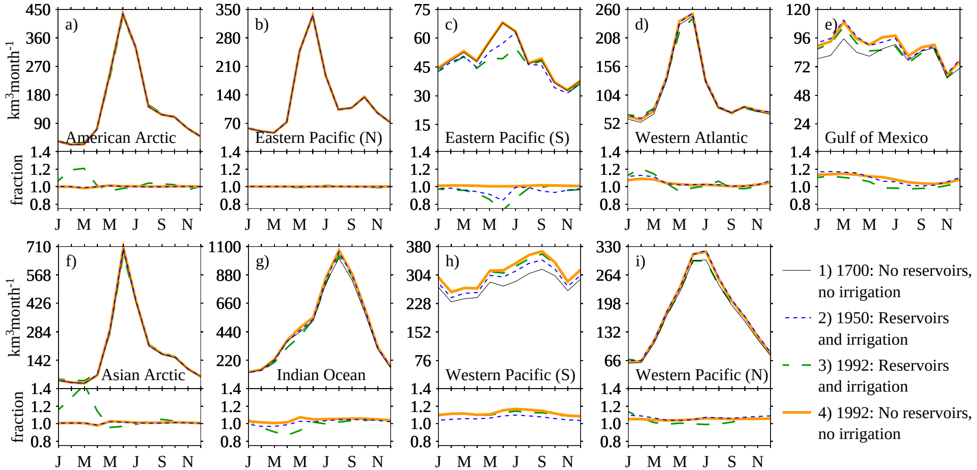

Fig. 7. Effects on freshwater fluxes reaching the oceans. **(a)** represents rivers draining northwards to the Arctic Ocean in the North American region (including Hudson Bay), **(b)** and **(c)** represent rivers draining North America to the Pacific Ocean north and south of 49 N, respectively. **(d)** represents rivers draining North America to the Atlantic Ocean, **(e)** represents rivers draining to the Gulf of Mexico, **(f)** represents rivers draining northwards to the Arctic Ocean in the Asian region, **(g)** represents rivers draining Asia to the Indian Ocean, and **(h)** and **(i)** represent rivers draining Asia to the Pacific Ocean north and south of the Tropic of Cancer, respectively. The lower panels show the results of simulations 2, 3 and 4 divided by simulation 1.

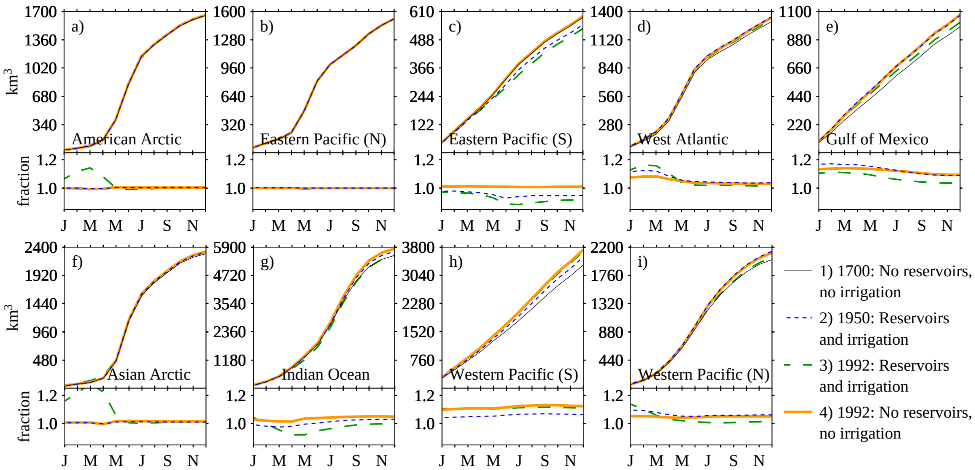

Fig. 8. Accumulated volume freshwater reaching the oceans. **(a)** represents rivers draining northwards to the Arctic Ocean in the North American region (including Hudson Bay), **(b)** and **(c)** represent rivers draining North America to the Pacific Ocean north and south of 49 N, respectively. **(d)** represents rivers draining North America to the Atlantic Ocean, **(e)** represents rivers draining to the Gulf of Mexico, **(f)** represents rivers draining northwards to the Arctic Ocean in the Asian region, **(g)** represents rivers draining Asia to the Indian Ocean, and **(h)** and **(i)** represent rivers draining Asia to the Pacific Ocean north and south of the Tropic of Cancer, respectively. The lower panels show the results of simulations 2, 3 and 4 divided by simulation 1.

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