

The Global Water Cycle

Taikan Oki

Institute of Industrial Science, University of Tokyo, Meguro, Tokyo, Japan

Dara Entekhabi

Massachusetts Institute of Technology, Cambridge, Massachusetts

Timothy Ives Harrold

Research Institute for Humanity and Nature, Kamigyo, Kyoto Japan

The global water cycle consists of the oceans, water in the atmosphere, and water in the landscape. The cycle is closed by the fluxes between these reservoirs. Although the amounts of water in the atmosphere and river channels are relatively small, the fluxes are high, and this water plays a critical role in society, which is dependent on water as a renewable resource. On a global scale, the meridional component of river runoff is shown to be about 10% of the corresponding atmospheric and oceanic meridional fluxes. Artificial storages and water withdrawals for irrigation have significant impacts on river runoff and hence on the overall global water cycle. Fully coupled atmosphere-land-river-ocean models of the world's climate are essential to assess the future water resources and scarcities in relation to climate change. An assessment of future water scarcity suggests that water shortages will worsen, with a very significant increase in water stress in Africa. The impact of population growth on water stress is shown to be higher than that of climate change. The virtual water trade, which should be taken into account when discussing the global water cycle and water scarcity, is also considered. The movement of virtual water from North America, Oceania, and Europe to the Middle East, North West Africa, and East Asia represents significant global savings of water. The anticipated world water crisis widens the opportunities for the study of the global water cycle to contribute to the development of sustainability within society and to the solution of practical social problems.

1. INTRODUCTION

Compared with other planets, the Earth system is unique in that water exists in all three phases, *i.e.*, water vapor, liquid water, and solid ice. Although the amount of water vapor is relatively small, large amounts of latent heat are released during

the phase change to liquid water; therefore the water cycle is closely linked to the energy cycle [Oki, 1999]. The water cycle is also closely related to the Earth's biogeochemical cycles, particularly of carbon and nitrogen. Water is the key that holds and ties these interacting and closely coupled cycles together. Water also interacts with topography, and transports sediment to oceans.

In this paper, the existence of water on Earth and the components of the global water cycle are briefly described, with an emphasis on the role of rivers, and the depiction of rivers

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within global models. An assessment of future water resources is presented, focusing on changes in runoff due to climate change, and changes in water stress due to changes in population and per capita demand. The virtual water trade, which significantly eases the limitations of water scarcity in many arid regions, is also considered.

1.1 Water on the Earth

The total volume of water on or near the Earth's surface is estimated as approximately $1.4 \times 10^{18} \text{ m}^3$, corresponding to a mass of $1.4 \times 10^{21} \text{ kg}$. Compared with the total mass of the Earth ($5.974 \times 10^{24} \text{ kg}$), water constitutes only 0.02% of the planet, but it is critical for the survival of life, and the Earth is consequently called "the Blue Planet" and "the Living Planet." Approximately 70% of its surface is covered with the salty water of the oceans. Some of the remaining surface is covered by fresh water (lakes and rivers), solid water (ice and snow), and vegetation (which implies the existence of water). Even though the water content of the atmosphere is comparatively small (approximately 0.3% by mass and 0.5% by volume of the atmosphere), approximately 60% of the Earth is always covered by cloud [Rossow et al., 1993].

The reserves of water in the Earth's water cycle are shown in Table 1 (based on Table 9 in Korzun, 1978). The proportion in the ocean is dominant (96.5%). Other major reserves are glaciers and permanent snow cover, and ground water. The proportion of water stored in the atmosphere, soil, and in river channels is very small, and the residence times are short, but, of course, this transient water plays a critical role in the global hydrological cycle.

1.2 Components of the Global Water Cycle

Figure 1 (from Oki 1999) schematically illustrates the components of the global water cycle, including storages (with volumes taken from Table 1) and approximate fluxes (for 1989–1992). The fluxes are calculated from precipitable water, water vapor transport, and convergence estimated using the European Centre for Medium-Range Weather Forecasts objective analyses, obtained as a 4-year mean [Hoskins 1989], and from the precipitation estimates of Xie and Arkin [1996]. The runoff flux is estimated at the land/sea boundary and includes a subsurface component of approximately 10% of the flow. These fluxes are only approximations and they will be improved by more precise measurements. However, on a global

Table 1: World water reserves

Form of water	Covering Area (km^2)	Total Volume (km^3)	Mean Depth (m)	Share of Volume (%)	Mean Residence Time
World oceans	361 300 000	1 338 000 000	3 700	96.539	2 500 years
Glaciers and permanent snow cover	16 227 500	24 064 100	1 463	1.736	56 years
Ground water ^a	134 800 000	23 400 000	174	1.688	8 years
Gound ice in zones of permafrost strata	21 000 000	300 000	14	0.0216	
Water in lakes	2 058 700	176 400	85.7	0.0127	
Soil moisture	82 000 000	16 500	0.2	0.0012	
Atmospheric water	510 000 000	12 900	0.025	0.0009	9 days
Marsh water	2 682 600	11 470	4.28	0.0008	
Water in rivers	148 800 000	2120	0.014	0.0002	18 days
Biological water	510 000 000	1 120	0.002	0.0001	
Total water reserves	510 000 000	1 385 984 610	2 718	100.00	

^a excluding Antarctic groundwater (approximately $2 000 000 \text{ km}^3$).

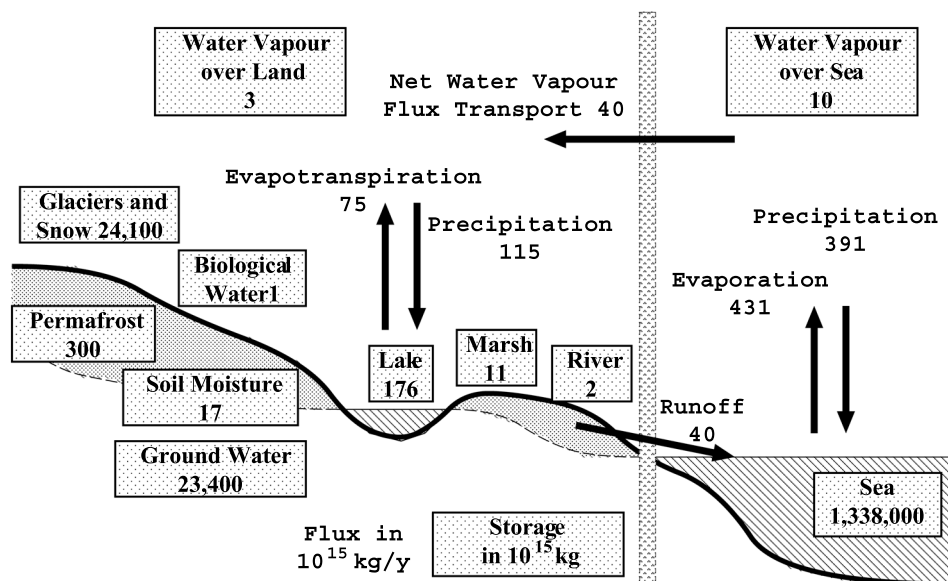


Figure 1. Schematic illustration of the water cycle on the Earth. Water storages (from Table 1) are indicated by boxes. Approximate fluxes (for 1989–1992) are represented by arrows.

scale, river runoff is about 8% of the atmospheric flux due to evaporation and precipitation.

The fluxes shown in Figure 1 are important for water resources assessment, because most social applications ultimately depend on water as a renewable and sustainable resource. Further, the current challenge is to estimate the variability of these fluxes at fine spatial and temporal scales. The regional impacts of variability can be severe, and include extreme weather events, floods, and droughts. The prediction of such variations in the global water cycle is one of the most urgent issues in modern hydrology.

Some important components of the global water cycle are now briefly introduced.

- *Water vapor* is the major absorber in the atmosphere of both short-wave and long-wave radiation. Condensation of water vapor releases a large amount of latent heat (2.5×10^6 J/kg), warming the atmosphere, and affecting atmospheric circulation.
- *Liquid water in the atmosphere* is the result of condensation. *Clouds* significantly affect radiation fluxes in the atmosphere and at the Earth's surface. *Precipitation* is highly variable in both space and time. It drives the hydrological cycle on the land surface and changes surface salinity in the ocean.
- *Evapotranspiration* is the return flow of water from the Earth's surface to the atmosphere and provides latent heat flux from the surface. Evapotranspiration is affected by atmospheric and soil conditions, and by vegetation.
- *Soil moisture* influences the energy balance at the land surface, as a lack of available water suppresses evapotranspiration and changes surface albedo. Soil moisture also affects runoff and infiltration.

- *Vegetation* can transpire water from deep soil layers, and affect the diurnal and seasonal cycle of evapotranspiration. Vegetation also modifies the surface energy and water balance by altering the surface albedo and by intercepting precipitation.

- *Snow cover* has special characteristics: snow may be accumulated, its albedo is high, and the surface temperature will not rise above 0°C until the completion of snow melting. Consequently the existence of snow cover significantly changes the surface energy budget. A snow surface typically reduces the aerodynamic roughness, so that it may also have a dynamical effect on the atmospheric circulation.

- *Ground water* contributes to runoff, especially during dry periods. Deep ground water may also reflect the long term climate.

- *Runoff* returns water to the ocean. The amount of water carried by rivers is smaller than that carried by the atmosphere and oceans, yet it is not negligible. Runoff into oceans is important for the fresh water balance and the salinity of the oceans.

- *The Oceans* are a major sub-system of the global water cycle. Even though classical hydrology has traditionally excluded ocean processes, the global hydrological cycle is never closed without them. The ocean circulation carries huge amounts of energy and water. Surface ocean currents are driven by surface winds, and the atmosphere itself is sensitive to sea surface temperatures. Temperature and salinity determine the density of ocean water, which contributes to overturning and the deep ocean general circulation.

The last column of Table 1 presents some values of the global mean residence time of water, which vary from a few

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days to thousands of years. The global mean residence times are a direct function of storage volumes and flux rates. There can be large regional variations in residence times, but they provide a broad indication of the susceptibility of each reserve to pollution, and to measures to improve water quality.

Precipitation, as stated above, drives the hydrological cycle on the land surface. Plate 1 illustrates the global distribution of mean annual precipitation for 1986–1995 from the forcing data for the Global Soil Wetness Project (GSWP) Phase II [IGPO, 2002]. The high spatial variability of precipitation can be clearly seen. The spatial variability of the runoff that results from this precipitation is also high. Plate 2 illustrates the annual mean runoff ratio for 1986–1995 estimated by a simple land surface model with forcing data from GSWP Phase II. The spatial distribution of the runoff ratio is partially influenced by the distribution of precipitation shown in Plate 1, but it is also influenced by the seasonal pattern of rainfall and potential evaporation, and by the characteristics of the land surface, such as topography and land cover. The runoff shown in Plate 2 does not disappear; it is conveyed to the oceans via rivers. The role of rivers within the global water cycle is discussed in the next section.

2 RIVERS IN THE GLOBAL WATER CYCLE

Rivers and their management are critical to the supply of fresh water in many parts of the world. Rivers are ecosystems of global importance, and much of hydrology is focused on understanding and modeling these systems. Rivers also have

a key role in the global water cycle. Rivers carry water, sediment, chemicals, and various nutrients from continents to seas. The fresh water supply to the ocean has an important effect on the thermohaline circulation, because it changes the salinity and thus the density of the oceans, and it also influences the formation of sea ice.

Annual fresh water transport to and from the oceans is shown in Table 2. The net atmospheric flux is estimated using four dimensional data assimilation data [Hoskins 1989]. River discharge is estimated by the bucket model [Manabe, 1969] with forcing data provided by GSWP Phase II, except the estimates for Antarctica use water vapor flux as a proxy for runoff. The total annual river discharge balances with the atmospheric water vapor flux convergence.

The annual water flux in the meridional direction for 1989–1992 has also been estimated, with the results shown in Plate 3 (from Oki et al., 1995). Transports by the atmosphere and by the ocean have almost the same absolute values at each latitude but with different signs. The transport by rivers is about 10% of these other global fluxes. The negative (southward) peak by rivers at 30° S is mainly due to the Parana River in South America, and the peaks at the equator and 10° N are due to rivers in South America, such as the Magdalena and Orinoco. Large Russian rivers, such as the Ob, Yenisey, and Lena, carry freshwater towards the north between 50–70° N. These results indicate that hydrological processes over land play a significant role in the overall global circulation, not only by the exchange of energy and water at the land surface, but also through affecting the water balance of the oceans.

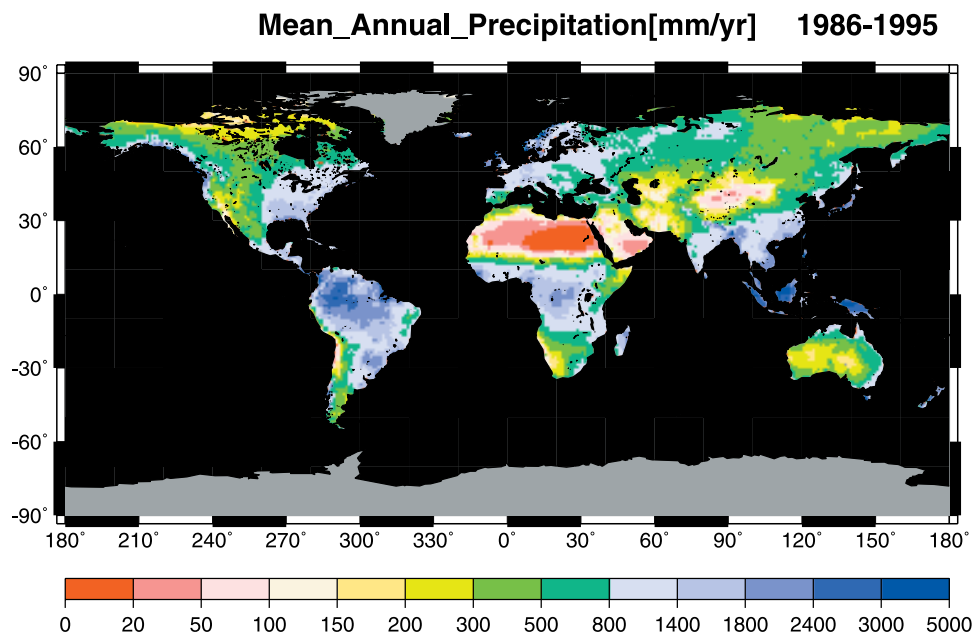


Plate 1. Mean annual precipitation (mm/y) for 1986-95 from the forcing data for the Global Soil Wetness Project Phase II.

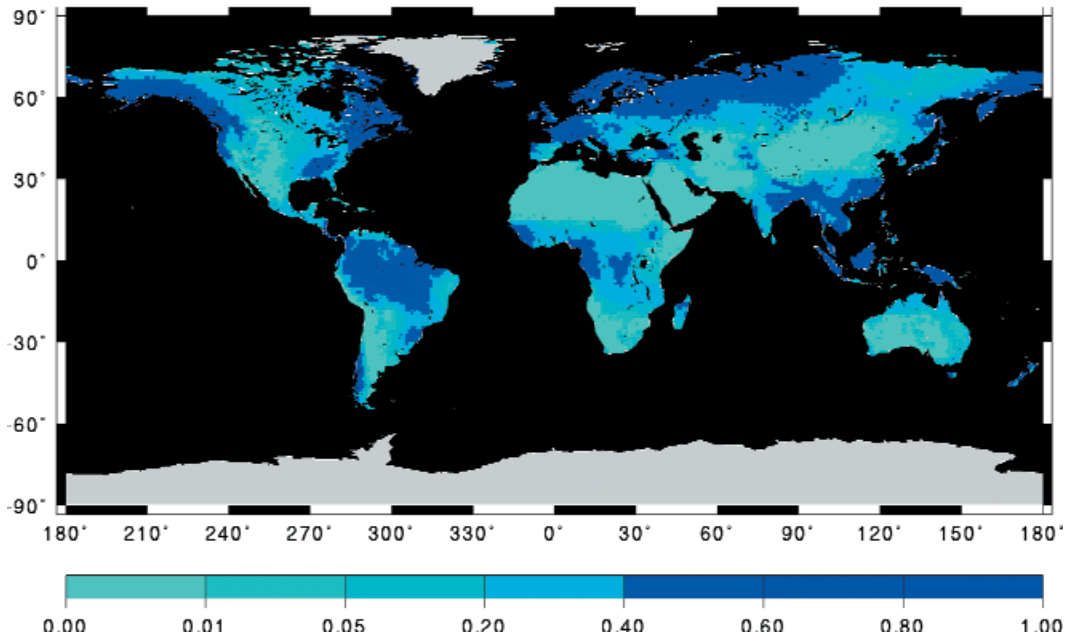


Plate 2. Annual mean runoff ratio for 1986-95 estimated by a simple land surface model with forcing data from the Global Soil Wetness Project Phase II.

2.1 Classification of river representation in GCMs

Based on the arguments presented above, it is obvious that rivers should be included in modeling of the climate system.

The role of rivers within a General Circulation Model (GCM) is to receive runoff from precipitation, to transport the runoff downstream, and to discharge the runoff back into the ocean, thus closing the lower section of the water cycle that is depicted

Table 2: Annual fresh water transport (10^{15} kg/y) to and from the oceans

	North Pacific	South Pacific	North Atlantic	South Atlantic	Indian Ocean	Arctic Ocean	Internal Drainage	Total
Asia	4.36	0.70	0.16		3.17	2.18	0.36	10.94
Europe			3.51			1.20	0.70	5.41
Africa			1.38	2.41	0.77		0.27	4.83
N.America	2.29		3.06			0.28	0.58	6.21
S.America	0.12	0.32	8.19	2.58			0.08	11.30
Oceania		1.53			0.37		0.03	1.94
Antarctica		(1.0)		(0.1)	(0.8)			(1.9)
Total River Discharge	6.78	2.56	16.30	4.99	4.32	3.66	2.02	40.62
(with Antarctica)	6.78	3.56	16.30	5.09	5.12	3.66	2.02	42.52
Net Atmospheric Flux	9.9	-11.1	-12.7	-14.0	-14.0	2.2	-2.02*	-41.72
Net Fresh Water Transport	16.68	-7.54	3.6	-8.91	-8.88	5.86		0.8 ^a

^aAssumed to match internal drainage, for mass balance purposes. In reality, this should be zero.

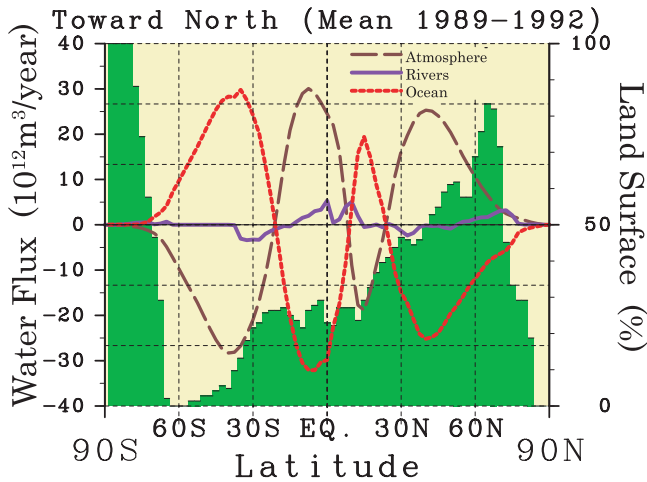


Plate 3. Annual water flux in the meridional direction by atmosphere, ocean, and rivers, 1989-1992. The background shading shows the percentage of the Earth's surface that is land, at each latitude.

in Figure 1. Table 3 (from Oki et al., 1999) shows a classification of the level of representation of rivers within GCM simulations, based on the destination of the river discharge, whether river routing is used, and whether interactions at downstream grid boxes occur. Level -1 through 0.5 are used for short term weather forecasting. For a coupled ocean-atmosphere model, level 1 representation of rivers may be adopted in order to close the mass balance of water in the model. A few GCMs use level 2 coupling [Miller et al., 1994; Sausen et al., 1994; Kanae et al., 1995].

Level 3 representation of rivers considers the effect of both artificial and natural water re-distribution from a river channel to the surrounding land surface. Runoff from an upstream grid box can evaporate at a downstream grid box by such an approach.

Even though the effect may be regional, the process should change the water and energy balance of the neighboring land

surface and have some effect on the climate system. Efforts to model these processes using fully coupled (level 3) atmosphere-land-river-ocean models are needed, and improvements to Land Surface Models and river routing schemes are required in order to achieve this objective.

The challenge to accomplish the level 3 coupling is mainly due to the uncertainties associated with modeling anthropogenic activities, such as water withdrawals for irrigation and the regulation of river flow by the operation of artificial reservoirs. The total capacity of artificial reservoirs is estimated as 8,000 km³ [Vörösmarty et al., 1997], which is large enough to affect the global river discharge of approximately 40,000 km³/y globally.

2.2 Digital Rivers in GCMs

At least three components are required in order to describe digital rivers in GCMs.

These are;

- a river routing scheme,
- information on the direction of the lateral water movement (a global river channel network), and
- river discharge data.

River routing schemes are commonly based on the one-dimensional Navier-Stokes equation. Because of the limitations both in obtaining all the necessary coefficients and in the computational burden, simplified equations, consisting only of mass conservation and the balance of friction with gravitational forcing, are widely used.

Global river channel networks are reported in Miller et al. [1994], Sausen et al. [1994], Kanae et al. [1995], and Vörösmarty et al. [1997]. More recently, Oki and Sud [1998] prepared a global river channel network in 1° x 1° grid boxes, named the Total Runoff Integrating Pathways (TRIP). River basin areas are represented in TRIP with root mean square error of ±10%, and the ratio of the river length in TRIP com-

Table 3: Representation of river processes in General Circulation Models

Level of Representation	Destination of Discharge	Timing
-1	Nowhere (it disappears)	Immediately
0	All ocean grids	Immediately
0.5	Nearest ocean grid	Immediately
1	Designated river mouth	Immediately
2	Designated river mouth	With time lag (river routing)
3	Level 2 + interactions at downstream grid boxes	

pared to the actual length is considered. TRIP is available to the public and has been used in various research studies, such as Chapelon et al. [2002] and Oki et al. [2003a], and included in general circulation models at the Hadley Centre (UK), Centre National de Recherches Meteorologiques, Meteo-France (France), and the Center for Climate System Research (CCSR) in the University of Tokyo (Japan). A part of TRIP in the Asian region is shown in Plate 4 (from Oki and Sud, 1998).

Another requirement for digital rivers is observed discharge data for the validation of the model. Observed river runoff represents integrated water fluxes over large areas. Therefore river runoff data should be used for the validation of GCM simulations and for assessments of variations of hydrologic cycles on a global scale.

Plate 5 shows the mean annual runoff for 1961–90 (from Oki et al., 1999). The plate is derived purely from observational data at river discharge gauging stations, with templates based on 1 degree mesh TRIP. The East-West transition of the runoff in North America can be seen; high runoff values are found in South America and Southeast Asia.

The negative runoff in some rivers, such as the Indus, Colorado, and other desert rivers, attract attention. Negative runoff occurs when downstream river discharge is less than upstream river discharge. Physically, negative runoff indicates that evapotranspiration exceeds precipitation in that river basin pixel. This situation often occurs artificially due to the diversion of river water to surrounding areas for irrigation, etc. Such anthropogenic effects are very important in most of the world's river

basins, and cannot be considered without level 3 coupling of an atmosphere-land-river-ocean model. Modeling of socially relevant issues, such as the termination of the river flow at the lower reach of the Yellow River in China, will not be possible without level 3 coupling. Such coupling will also increase confidence in our ability to properly assess current and future world water resources.

3 FUTURE WORLD WATER RESOURCES

Water resources are under serious pressure in some regions of the Earth, and the situation is likely to worsen [Cosgrove and Rijsberman, 2000]. At the June 2003 G8 summit in Evian, France, the water crisis was addressed as a problem of the utmost gravity. “Water: a G8 Action Plan” is a summit consensus statement that appears immediately after the “Chair’s Summary”.

The estimation of the current level of water stress is important for reliable projections of the severity of the water crisis into the future. Global analyses of water scarcity have been carried out by Takahashi et al. [2000] and Vörösmarty et al. [2000]. Oki et al. [2001] presented water scarcities on a 0.5 degree by 0.5 degree grid for the globe.

Assessment of future water resources involves assessment of climate change, population growth, and changes in demand. The supply side of water resources for both present and future conditions can be directly taken from runoff simulated by a GCM. However, GCMs suffer biases in calculating water

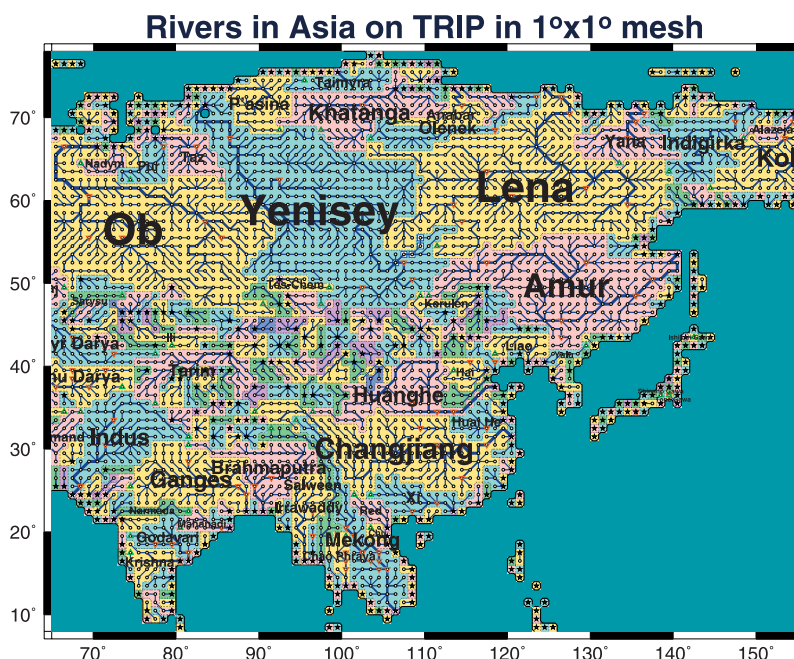


Plate 4. A part of the 1° grid Total Runoff Integrating Pathways (TRIP), in the Asian region.

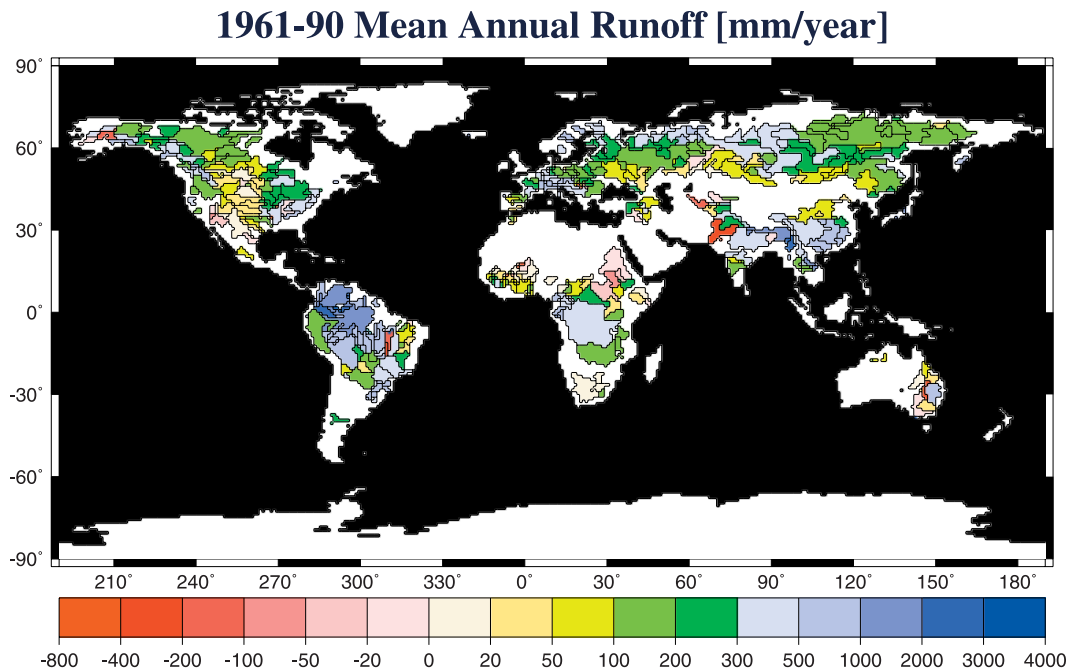


Plate 5. Mean annual runoff (mm/y) based on gauge data mean 1961-1990.

cycles, and direct values from GCMs are not frequently used. Instead, the change between current and future conditions from GCM studies can be applied to observed or best estimated current precipitation and temperature to produce future scenarios (see, for example, Arnell, 2004; Alcamo et al., 2003; Wallace, 2002). The modified precipitation and temperature are then used as future climatic inputs to a macro scale hydrological model, and future river runoff is calculated. However, such a procedure may have some inconsistencies with the original runoff simulation by GCMs.

In Oki et al. [2003a], projection of future world water resources was carried out by using current runoff estimated by land surface models (LSMs) and adding or subtracting the change in runoff estimated by a general circulation model (GCM), and considering future water withdrawals estimated by trend analysis. Results from Oki et al. [2003a] are discussed in sections 3.1 and 3.2.

3.1 Future Water Availability

To estimate the current runoff distribution on a global scale, offline runs by 11 different land surface models (LSMs) were used [Oki et al., 1999]. Offline simulation means LSMs are not coupled with the atmospheric component of GCMs but are instead driven by “forcing” data, with no feedback to the atmospheric circulation. Forcing data from ISLSCP were used (International Satellite Land Surface Climatology Project; Meeson et al., 1995). The data are based on observations of

precipitation and radiation at the surface and from space, with data assimilation techniques applied to cover the regions with sparse monitoring networks. TRIP [Oki and Sud, 1998] was used for the river routing calculations to convert runoff from LSMs into river discharge. The estimated current annual discharge corresponded fairly well with river runoff observations [Oki et al. 2001], but was smaller compared to previous estimates by approximately 20%, mainly due to reduced bias in the forcing precipitation.

A CCSR/NIES atmospheric general circulation model (AGCM) [Numaguti et al., 1997] was run with boundary conditions of sea surface temperature in both 1990 and 2060, with sea surface temperatures for 2060 obtained from a coupled ocean-atmospheric general circulation model (AOGCM) run for doubled carbon dioxide conditions. The horizontal resolution of the AGCM was approximately 100km*100km globally. The simulated daily runoff from the AGCM was then routed using TRIP. The differences in annual mean runoff between 1990 and 2060 are shown in Plate 6 (from Oki et al. 2003a).

For this particular simulation, the Asian monsoon is enhanced due to the enhancement of the temperature difference between the Indian Ocean and Eurasia, and runoff is increased in the Indian sub-continent, the western part of the Indo-China Peninsula, northern China, and central and western Africa. Decreases in runoff are projected in central China and Europe. However Plate 6 is based on one possible climate scenario, based on modeling from a single GCM. The

Annual Change in River Discharge

[$10^6 \text{ m}^3/0.5^\circ\text{grid cell}$]

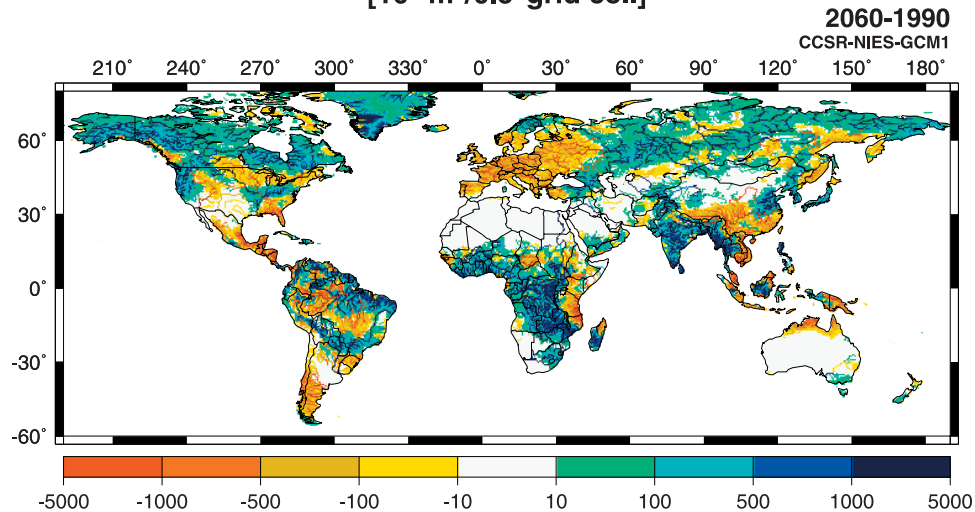


Plate 6. The difference in runoff (10^6 m^3 in each $0.5 \times 0.5^\circ$ grid box) between 1990 and 2060, based on one possible climate scenario for 2060.

uncertainties involved with future climate scenarios are very high, and different GCMs will probably produce different patterns to the one presented here.

3.2 Future Water Scarcity

The assessment of water scarcity in Oki et al. [2003a] adopted the water scarcity index R_{ws} of Falkenmark et al. [1989], which is the ratio of the annual water withdrawal W to

the available annual water Q , as used by United Nations [1997] and Vörösmarty et al. [2000]. The current water withdrawals estimated in Oki et al. [2001] were used as the baseline for the future prediction of the water withdrawals. The future withdrawals were estimated separately for municipal, industrial, and agricultural water usages. The increase in irrigation withdrawal was assumed proportional to population growth. The resulting global distribution of projected R_{ws} in 2050 is shown in Plate 7 (from Oki et al., 2003a).

Annual Withdrawal-to-Availability Ratio

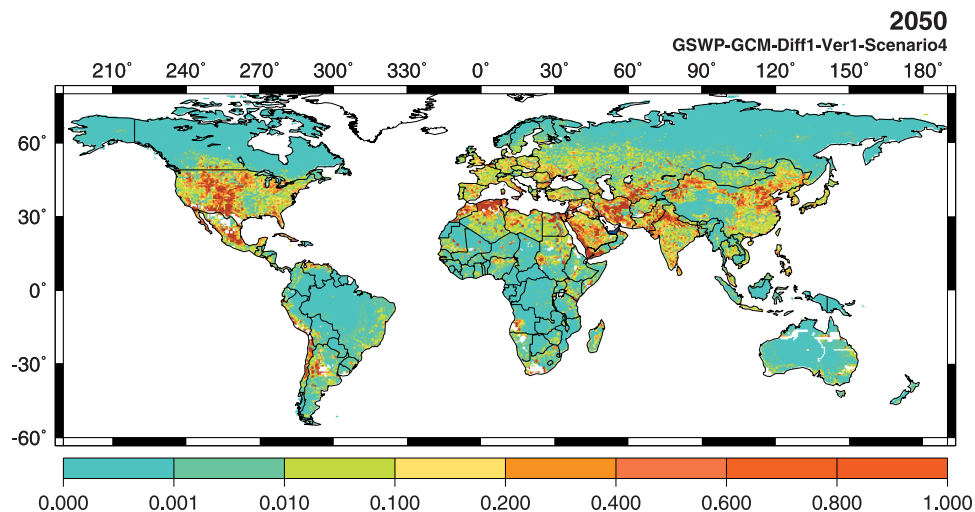


Plate 7. The projected global water scarcity R_{ws} (water withdrawal to availability ratio) in 2050.

Generally the severity of water scarcity is judged as:

$$\begin{aligned} R_{ws} < 0.1 & \text{ no water stress} \\ 0.1 = R_{ws} < 0.2 & \text{ low water stress} \\ 0.2 = R_{ws} < 0.4 & \text{ moderate water stress} \\ 0.4 = R_{ws} & \text{ high water stress} \end{aligned}$$

Following this criteria, it is evident from Plate 7 that water scarcity will be severe in the river basins of Yellow, Indus, Ganges, and Amu-Darya, and in the middle west of the United States. These scarcities are generally similar to the current situation. However the scarcity anticipated in Africa is a change from the current situation. Rapid increases in African water withdrawals are projected according to the population growth estimated by the United Nations. Such sudden increases in R_{ws} should demand the development of infrastructure and management systems, and the situation will be serious if these objectives cannot be achieved.

The world population living in regions of no water stress, low water stress, moderate water stress, and high water stress in 1995 and 2050 is shown in Table 4 (from Oki et al., 2003a). The contributions of population growth, climate change, and per capita increases in water demand to the figures for 2050 are also shown in Table 4. Population growth has the largest impact on the increase in people under high water stress levels, with the impact of climate change being of lesser importance. Based on the GCM simulation used in this study, the water stress level is somewhat eased by climate change effects. This is opposite to the result by Vörösmarty et al. [2000] in which the population under high water stress increases slightly if the impact of climate change is considered. The difference between the two studies may be due to the large uncertainties associated with GCM projections of climate change; nonetheless both studies agree that the impact of population growth on water stress is higher than the impact of climate change.

4 THE VIRTUAL WATER TRADE

The concept of “Virtual Water” has been developed to explain how physical water scarcity in countries in arid regions

is relaxed by importing water-intensive commodities [Allan, 1997]. The real water cycle is somewhat different from the natural water cycle, even on the global scale, in the Anthropocene [Crutzen, 2002], and the virtual water trade should be taken into account when discussing the global water cycle and water scarcity.

The unit requirement of water (UW) to produce each commodity should be estimated so that the virtual water trade can be quantified [Wichelns, 2001]. The database of UW can be utilized for assessment of water demand in the future [Yang and Zehnder, 2002]. Estimation of UW is not difficult:

$$UW = \frac{TWA}{TWE}$$

where TWA is total water use to produce the goods and TWE is the weight (or the value) of the goods

However, there is no consensus on the definition of “total water use” or “the weight of the goods”. Some researchers only consider on-farm evapotranspiration, but others count water losses such as irrigation canal seepage and return flow. The weight of the goods can be considered as either gross weight or edible weight.

UW is highly dependent on the crop yield per area and is different in each country and changes with time. Since the original idea of virtual water is how much water can be saved in the importing country, the UW of the importing country should be used to estimate the how much virtual water is imported. In this aspect, it is obvious that “virtual water” is “virtually required water” in its original sense, and we may call the water really used in the exporting country “really required water” or “real water” in the same way.

From this point of view, “real water” in exporting countries and “virtual water” in importing countries generally do not correspond quantitatively. For example, one kilogram of soy bean is produced using 1.7 tons of water in the United States; however, it requires 2.5 tons of water if the same amount of soy bean is grown in Japan. In this case, 1.7 ton of “real water” in

Table 4: World Population (billion people) under each Water Stress Level projected in 2050

Stress Level	Current (1995)	Future		
		Population Growth Only	+Climate Change	+Unit Demand Increase
High Water Stress	1.7	2.66	2.43	2.51
Moderate Water Stress	0.6	0.91	0.93	0.97
Low Water Stress	0.6	0.94	0.96	1.00
No Water Stress	2.8	4.31	4.45	4.28

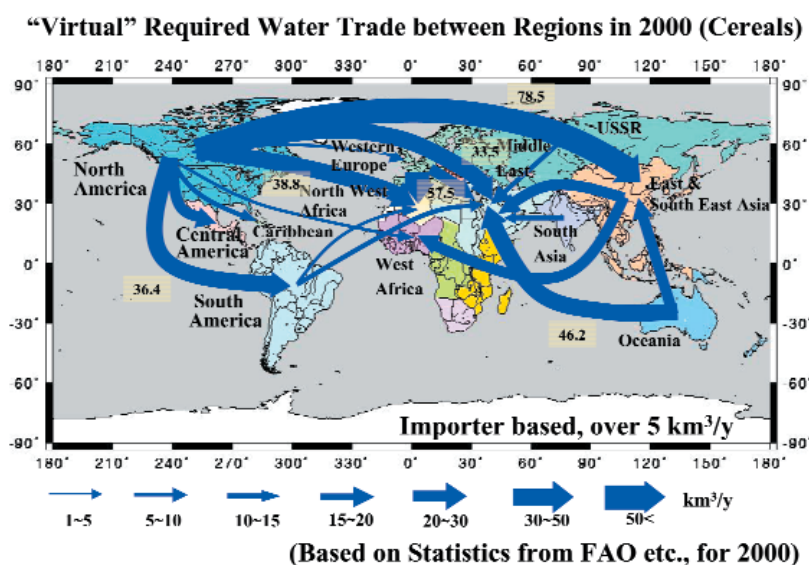


Plate 8. Annual virtually required water (virtual water) trade (km³/y) in year 2000 estimated for major crops of wheat, rice, maize, and barley.

the United States will be 2.5 ton of virtual water in Japan, associated with the import of 1 kilogram of soy bean.

Global estimation of the virtual water trade is now considered (from Oki et al., 2003b).

4.1 Global Virtual Water Flow

Global “virtual” and “real” water flows associated with major cereal (wheat, rice, maize, and barley) trade was estimated for each country where statistics were available for year 2000, and summarized into 16 regions. The annual virtual water flows are presented in Plate 8 (from Oki et al., 2003b). The plate shows that the Middle East, North West Africa, and East & South East Asia are gathering virtual water. The sources of virtual water are North America, Oceania, and Europe.

4.2 Does Virtual Water Save Water Globally?

Generally crop yields and water efficiencies in exporting countries are higher than in importing countries. Consequently, “real water” in exporting countries tends to be smaller than “virtual water” in importing countries. For example, as mentioned above, 1 kilogram of soy bean corresponds 1.7 ton of “real water” in the United States and 2.5 ton of “virtual water” in Japan. In this sense, the virtual water trade of 1 kilogram of soy bean from the United States to Japan saves 0.8 ton of global water resources.

Table 5 (from Oki et al. 2003b) shows total global “virtual water” and “real water” international transfers for year 2000 for maize, wheat, rice, and barley, soy bean, chicken, pork,

and beef. Hoekstra and Hung’s [2002] estimates of “virtual water” for the 1995–1999 cereal trade are also shown in Table 5, labeled as “VW”. Hoekstra and Hung used global mean crop yield data to calculate VW (in contrast to Oki et al., who used country crop yield data wherever possible).

The total virtual water trade (imported virtual water) for the commodities in Table 5 is approximately 1,140 km³/y, however this corresponds to only 680 km³/y of real water, representing a water saving of 460 km³/y. The water savings are highest for crops and soybeans. It is interesting to see that the saving is less for chicken and pork, and is not significant for beef. This analysis provides a supporting argument for the globalization of trade; Table 5 claims that transferring commodities from water efficient regions to water inefficient regions will save global water resources. While the virtual water trade will not increase the total water resource, “saved” water in the importing country can be allocated to other purposes, such as municipal use and environmental use. However, one should be careful about interpreting these results since the idea of virtual water does not consider social, cultural, and environmental implications or limiting factors other than water.

5 CONCLUDING REMARKS

The global water cycle is essential in the Earth System. The ultimate goal of hydrological science is to increase understanding of the global water cycle through monitoring and modeling. The outcomes of hydrological research should be able to be used as tools to estimate, understand, and assess the water cycles on the Earth on various temporal and spatial

Table 5: Global virtual and real water transfer (km³/y) associated with crop and meat trade

	Estimates by IIS, University of Tokyo				IHE ^a
	Virtual Water	Real Water	Saved		VW
	(km ³ /y)	(km ³ /y)	(km ³ /y)	(%) to VW	(km ³ /y)
Maize	127.0	51.7	75.3	59	61.4
Wheat	464.2	270.9	193.3	42	209.8
Rice	185.6	110.7	74.9	40	106.8
Barley	91.5	38.4	53.2	58	34.0
Cereal Total	868.4	471.7	396.6	46	(412.0)
Soy bean	118.1	84.0	34.1	29	
Chicken	37.4	25.3	12.0	32	
Pork	28.3	19.6	8.7	31	
Beef	86.2	82.4	3.9	5	
Meat total	151.9	127.3	24.6	16	
Total	1138.3	683.0	455.3	41	

^aIHE: “Virtual Water Trade” [Hoekstra and Hung, 2002]

scales, and these tools should be accessible to other scientific disciplines, the general public, and decision makers.

New developments and continued operation of existing global water cycle monitoring systems are essential to promote science and contribute to society. Innovative satellite observing missions, such as the Global Precipitation Mission (GPM) and the Hydrosphere Satellite Mission (HYDROS), are planned and should be pursued in addition to the maintenance and integration of surface observational networks of hydrological stations.

According to the paradigm shift of research in natural sciences after the wide recognition of global environmental problems, it is the era for geosciences to study the real situation of the Earth, including the impacts of anthropogenic activities. Water cycles are one of the most exposed natural cycles, vulnerable to human impacts. Therefore hydrological science should study water cycles, their impact on human society, and anthropogenic impact on water cycles. Regional characteristics and historical circumstances should be specially considered.

Scientifically excellent research and socially relevant research are not necessarily exclusive, and the anticipated world water crisis widens the opportunities for excellent scientific research to contribute to the solution of practical problems.

International and interdisciplinary frame works are required for the promotion of the hydrological sciences. More collaboration within hydrological sciences and with other disci-

plines is crucial, and philosophical and institutional development of hydrological sciences is ongoing.

The term “sustainable development” is often mistakenly interpreted as meaning that development must continue; hence, the term has come in for some criticism. In fact, the term’s true meaning can be expressed as “the development of sustainability within society.” At the present juncture, the most important requirement for a sustainable global water cycle is that governments, NGOs, universities, and private enterprises pool their wisdom and build sustainability into society through a fusion of policies, systems, scientific knowledge, and technical support for water.

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Dara Entekhabi, Massachusetts Institute of Technology, Room 48-331, Cambridge, MA 02139, USA

Timothy Ives Harrold, Research Institute for Humanity and Nature, 335 Takashima-cho, Kamigyo-ku, Kyoto 602-0878, JAPAN

Taikan Oki, Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505 Japan