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Global runoff estimation by atmospheric water balance using ECMWF data set

T. OKI, K. MUSIAKE
Institute of Industrial Science, University of Tokyo, 7-22-1, Roppongi, Minato-ku, Tokyo 106, Japan
K. MASUDA
Department of Geography, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-03, Japan
H. MATSUYAMA
Department of Geography, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113, Japan

Abstract The global distribution of vapour flux convergence $-\nabla_H.\vec{Q}$ is estimated using the ECMWF (European Centre for Medium-Range Weather Forecasts) global analysis data for the period from 1985 to 1988. From the atmospheric water balance, the annual mean $-\nabla_H.\vec{Q}$ can be interpreted as precipitation minus evaporation. The zonal mean of the calculated $-\nabla_H.\vec{Q}$ shows good correspondence with past estimations. The $-\nabla_H.\vec{Q}$ is also compared with the runoff of large rivers. The multi annual mean of the GRDC (Global Runoff Data Centre) data set is used for the comparison. There are good relationships between atmospheric water balance and the runoff observations on the ground, especially in the northern hemisphere. The result indicates the importance of accurate routine observation of both atmosphere and river runoff. The global annual river discharge from all continents to the sea is estimated to be 170 mm year^{-1}.

INTRODUCTION

There are three research topics to be investigated by hydrologists in "Global Change" problems:

(a) Better understanding of the reality and the mechanism of global water circulation and balance. Such research will contribute to display the global hydrological data set which can be used for the validation of climate simulations.

(b) The development of climate models which can represent the regional scale water circulation and balance. It may include the development of a precise hydrological surface model at the GCM grid scale.

(c) The interpretation of the model forecast for social activities. There have been some attempts to investigate water resource change in river basins under the present global change scenario.

This study estimates river runoff using global atmospheric data by the atmospheric water balance method. The annual global value of river runoff, the latitudinal distribution and the annual river runoff in each large river basin are presented in this study. The results and the method presented here will contribute to investigations from the global scale to the basin scale.

It can also be expected that the deep understanding of the global water circulation and its variability would make it possible to forecast long term water resource changes. Therefore it is important to investigate the global water cycle and water balance, and to examine them at the river basin scale.

GLOBAL WATER BALANCE

The water balance at global scale is a traditional research subject of geographical hydrology, and there are many estimations of it. Korzun (1978) summarized such results, which were obtained by observations of precipitation and runoff at the surface, and calculated evaporation rate using climatological temperature over oceans.

On the other hand, the development of computational ability has made large amounts of data processing possible, and the atmospheric water balance method was applied for global water balance estimations by Bryan & Oort (1984) and Masuda (1988). The method was first used by Starr & Peixoto (1958). This study uses the method, and estimates large scale water balance referring to the runoff data observed at the surface.

Atmospheric water balance method

Water balance equation for an atmospheric column is :

$$\frac{\partial W}{\partial t}+\frac{\partial W_c}{\partial t} = -\nabla_H \cdot \vec{Q}-\nabla_H \cdot \vec{Q}_c+(E-P) \tag{1}$$

and that for a river basin is :

$$\frac{\partial S}{\partial t} = -\nabla_H \cdot \vec{R}_o-\nabla_H \cdot \vec{R}_u-(E-P) \tag{2}$$

Here W, W_c, $\vec{Q}$, $\vec{Q}_c$, E, and P represent precipitable water (column storage of water vapour), column storage of liquid and solid water, vertically integrated horizontally two-dimensional vapour flux, vertically integrated horizontally two-dimensional water flux in liquid and solid phase, evaporation, and precipitation, respectively. ∇_H represents the horizontal divergence. S represents the storage in the basin and $\vec{R}_o$, $\vec{R}_u$ represent the runoff and the groundwater movement.

Here are some assumptions used for annual water balance estimations:

(a) Interannual variation of atmospheric vapour storage is negligible (left-hand side of equation (1) is equal to 0).

(b) advection of water in liquid and solid phase ($\nabla_H.\vec{Q}_c$) is negligible in such a scale that can be resolved by the 2.5° latitudinal and longitudinal global grid point data used in this study.

(c) Interannual change of basin water storage ($\partial S/\partial t$) is negligible and all ground water movement is observed at the gauging point ($\nabla_H.\vec{R}_u = 0$).

From these assumptions, equation (1) and equation (2) make:

$$-\nabla_H \cdot \vec{Q} = (P-E) \tag{3}$$

$$-\nabla_H \cdot \vec{Q} = \nabla_H \cdot \vec{R}_o \tag{4}$$

Equations (3) and (4) mean that the vapour flux convergence, precipitation minus evaporation and runoff of that area are equal in annual water balance. Using these equations, global water balance can be estimated from atmospheric data of wind velocity and humidity.

(a) Annual global runoff distribution can be estimated by equation (4) using atmospheric data only.
(b) Global evaporation distribution can be estimated by equation (3) using additional precipitation equation (1).
(c) Variation of basin storage can be estimated from equation (2).

DATA ANALYSIS

Data description

ECMWF (European Centre for Medium-Range Weather Forecasts) objective analysis data by 4-dimensional assimilation system is used as the atmospheric data. River runoff observed at the ground is from GRDC (Global Runoff Data Centre) and also from the book of UNESCO (1969).

Thirty-five rivers which have basin areas greater than 300 000 km^2 were selected.

ECMWF data processing

Wind, temperature, relative humidity and pressure height are given in seven levels of 1000, 850, 700, 500, 300, 200, 100 (hPa) by 2.5° global grids, though relative humidity can be found only in the lower five levels. The time interval of the data is twice daily after 1985. The annual mean $-\nabla_H.\vec{Q}$ is estimated through:
(a) Extrapolation of the values at the ground surface using topographical data;
(b) Vertical integration and horizontal convergence calculation;
(c) Temporal integration.
Global altitude data set in 2.5° grids were also made and used for the computation. Vapour flux convergence is given in the units of (kg m^{-2} s^{-1}), it is converted into (mm year^{-1}) assuming the density of water to be 1.0, in order to make comparison with annual runoff easier.

RESULTS

Global annual runoff from whole continents

Global vapour flux convergence distribution is shown in Fig. 1. The data for the period 1985 to 1988 is used here because the homogeneity of the quality (Oki *et al.*, 1991). A zone of strong convergence occurs in the tropics, especially from Indian ocean to the western part of Pacific. Both sub-tropical oceans are divergence zones. Middle and high latitudes are generally zones of weak convergence.

The continents were divided into river basins (Fig. 2). According to Korzun (1978), land cover on the earth is about 29%, (31% in this model). Annual runoff from whole continents is calculated from Fig. 1 using the land-sea distribution of Fig. 2, and compared with past estimates (Table 1). Results of this study are very similar to FGGE-ECMWF, and relatively small compared with the results from basin water balance. The difference between $-\nabla_H.\vec{Q}$ and river runoff in Table 1 may be caused by

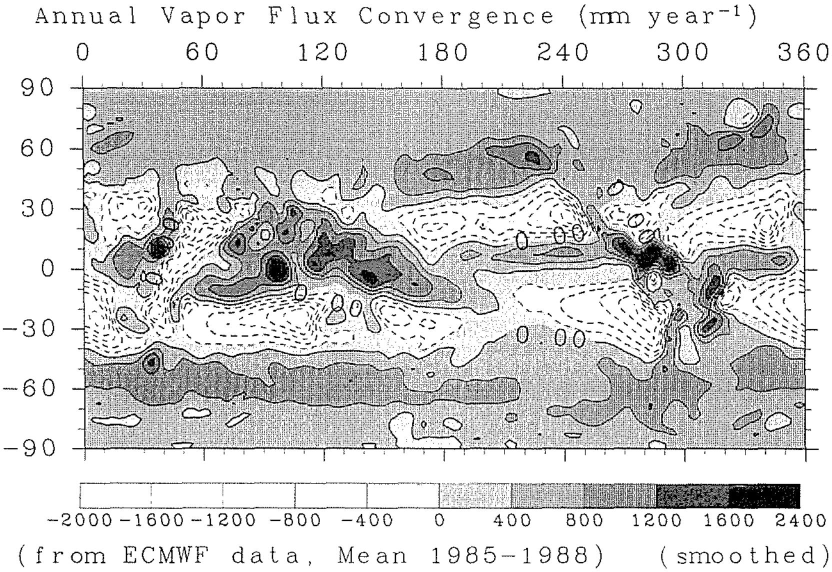

Fig. 1 Annual vapour flux convergence (mm year^{-1}), mean 1985-1988.

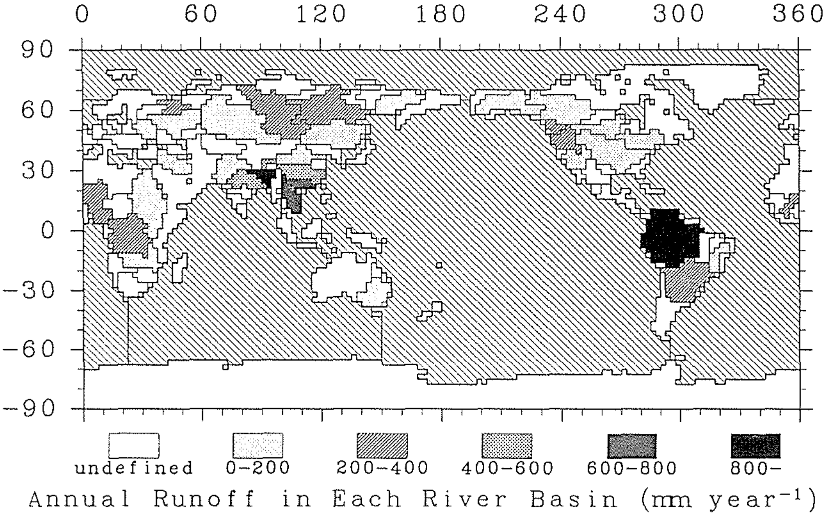

Fig. 2 Land-sea distribution and annual discharge of each river. Shading patterns indicate the range of the areal mean runoff for each river basin.

Table 1 Estimates of global annual runoff from whole continents (mm year^{-1}).

269	(Lvovitch, 1973)	Basin water balance
256	(Baumgartner & Reichel, 1975)	Basin water balance
303	(Korzun, 1978)	River runoff
42	(Bryan & Oort, 1984)	Atmospheric water balance, 1963-1974
152	(Masuda, 1988)	ECMWF data, year of FGGE(1979)
260	(Masuda, 1988)	GFDL data, year of FGGE(1979)
167	This study	ECMWF data, 1985-1988

the bias that the divergence of the wind is weak in the ECMWF objective analysis data set (Masuda, 1988).

Latitudinal distribution of global runoff

Figure 3 shows the zonal (east-west direction) mean of vapour flux convergence and the comparison with former results for the latitudinal distribution of precipitation minus evaporation. They have good agreement quantitatively, but the results of this study shows slightly larger excess of evaporation over precipitation in both sub-tropics.

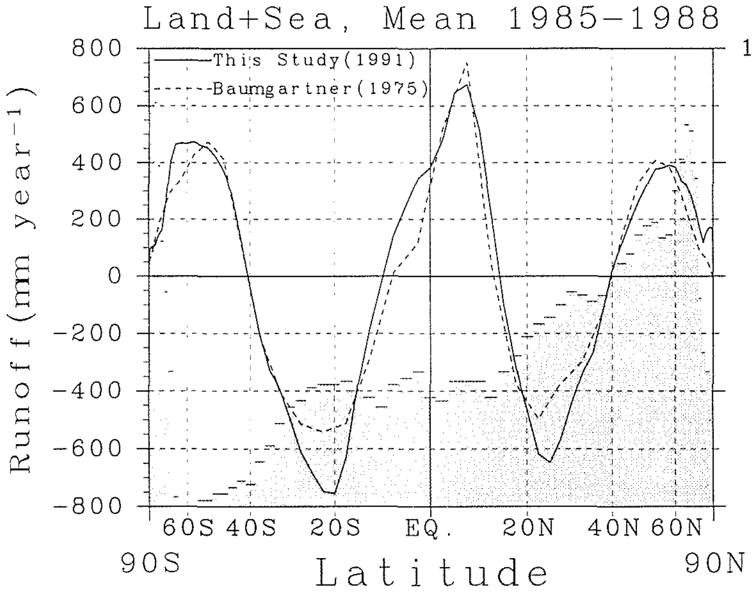

Fig. 3 Latitudinal distribution of global runoff (mm year^{-1}). Shaded columns show the percentage of land at each latitude.

Vapour flux convergence and river runoff

Annual vapour flux convergence is estimated in each river basin listed in Table 2, and the comparison with observed river runoff is shown in Fig. 4, using the index of the absolute difference between them. Runoff depth was calculated by dividing discharge volume by basin area and taking the temporal mean of all the data in the available period.

If the estimation error is evaluated as a ratio to the observed value, as one can see in the last column of Table 2, the ratio of the error (expected to be zero) is roughly within the range of 100%, but this index is not adequate for the rivers whose annual runoff is small, because the error is over emphasized.

There are some difficulties in the quantitative comparison between atmospheric vapour flux convergence and river runoff here:

(a) Vapour flux convergence is computed for the whole basin in the model topography,

Table 2 Large rivers in the world and annual runoff.

River	Station (GRDC)	GRDC	UNESCO (mm year^{-1})	$-\nabla_H \cdot \vec{Q}$	Error. (%)
Amazonas	Obidos	1057	1176	206	-81
Congo (Zaire)	Brazzaville		367	247	-33
Mississippi	Alton(Ill.)	205	186	114	-45
Nile	Khartoum	150	159	554	271
Ob	Salekhard	134	130	106	-21
Yenisey	Igarka	223	230	219	-2
Lena	Kusur	216	212	192	-11
Parana	Corrientes	264	382	484	83
Niger	Koulikoro	376	109	-70	-119
Amur	Komsomolsk	178	188	119	-33
Changjiang	Datong	431	(503)	627	46
Mackenzie	Norman wells	168	160	245	45
Volga	Volgograd	184	181	99	-46
Zambezi	Matundo-Cais	112		-283	-352
St.Lawrence	Cornwall	323	290	315	-3
Ganges	Paksey		434	-68	-116
Murray	Locks 9 Upper	8		-34	-519
Nelson	Bladder Rapids	76	92	176	132
Indus	Koti	92		-124	-235
Orinoco	Musinacio		935	373	-60
Yukon	Carmacks	35	255	513	1362
Danube	Ceatal Izmail	253	244	124	-51
Mekong	Mukdahan		693	914	32
Al-Furat	Hindiya		69	36	-47
Huanghe	Sanmenxia	6	(63)	-235	-4281
Brahmaputra	Pandu	1535	998	481	-69
Sao Francisco	Traipu	13	194	-748	-5656
Columbia	TheDalles, Oreg.	272	284	183	-33
Kolyma	Sredne-kolymsk	192	196	260	-35
Colorado	Lim.Inte.Norte	4	19	-60	-1753
Dniepr	Dniepr	101	93	106	5
Xijiang	Wuzhou	681	(682)	46	-93
Northern Dvina	Ust-Pinega	302	306	303	0
Magdalena	Calamar	856	1115	3987	366
Fraser	Hope	397	418	712	79

Error index indicates $-\nabla_H \cdot \vec{Q}$ − GRDC Runoff.

Data for Changjiang, Huanghe and Xijiang are from personal communications.

but runoff observation points do not always represent the whole basin runoff (e.g. Nile or Niger).

(b) The observation periods for atmospheric data and runoff are completely different.

(c) There are some difficulties in dividing the continents into river basins. In the case of small rivers, it is very hard to define a river basin accurately using 2.5° grids.

(d) The quality of runoff observation at each observation point is not known, there may be variations.

However the atmospheric vapour flux convergence and river runoff correspond more closely than expected. Figure 4 also shows that it is not always true that the larger a river basin is the better the atmospheric water balance method results.

One can see the correspondence between the vapour flux convergence and the river runoff in Fig. 5. The differences in basins in the mid-latitude to high-latitude of the

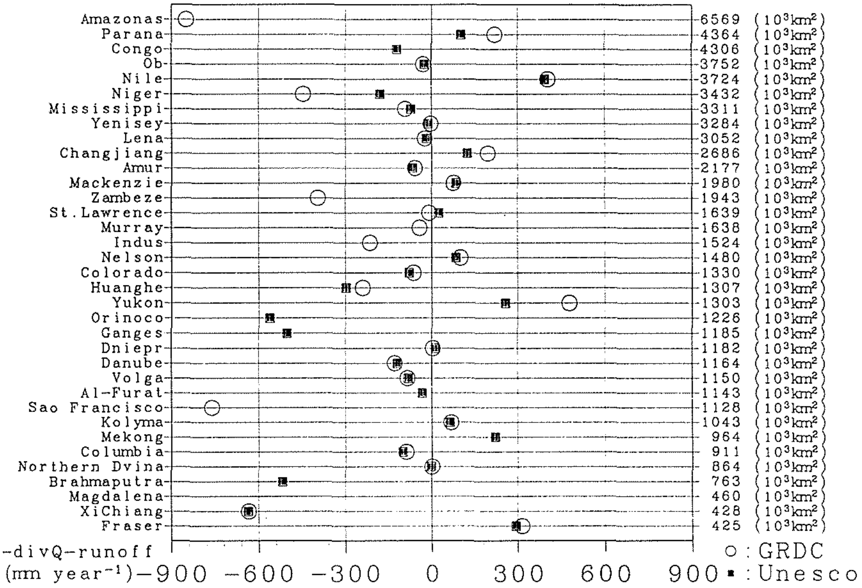

Fig. 4 Difference between vapour flux convergence and river runoff observation data of GRDC (○) or UNESCO(■).

northern hemisphere are much less than elsewhere. This distribution may reflect the quality and high density observations of the atmosphere. The result indicates the importance of the accurate routine observation of both atmosphere and river runoff.

Mean $-\nabla_H\cdot\vec{Q}$ of these 35 rivers weighted by their areas is about 220 (mm year^{-1}). This value is larger than that of $-\nabla_H\cdot\vec{Q}$ of whole continents, but it is still smaller than the mean runoff of these rivers, 314 (mm year^{-1}) by GRDC, and 365 (mm year^{-1}) by UNESCO (1969). These 35 river basins cover less than half of the land on the earth

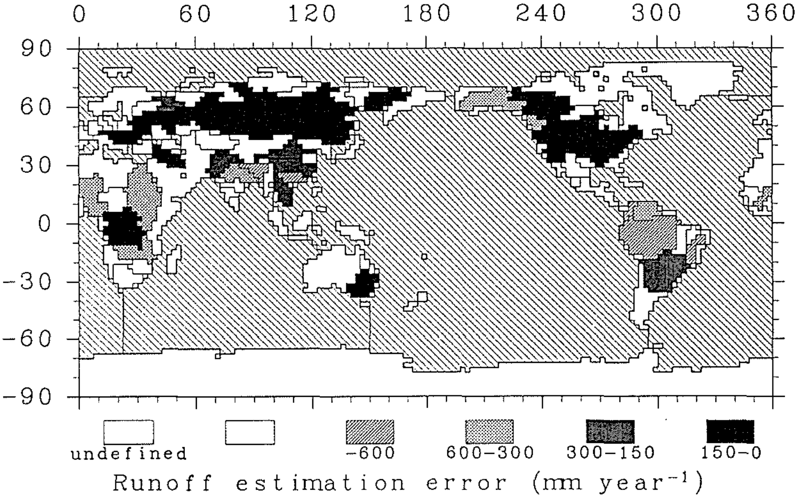

Fig. 5 Absolute difference between vapour flux convergence and river runoff observations in each river basin.

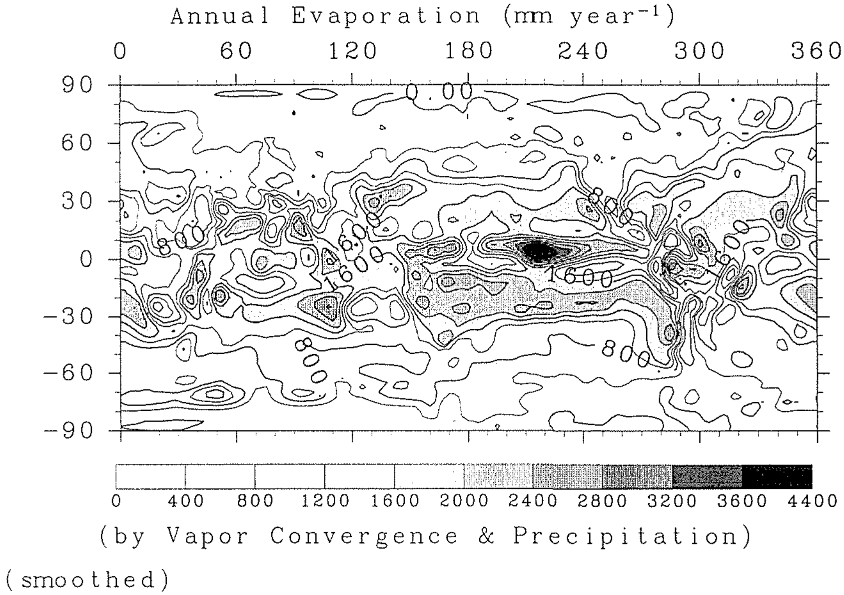

Fig. 6 Annual evaporation (mm year^{-1}), using atmospheric vapour flux convergence *from ECMWF data (4 years mean) and climatological precipitation data of Legates.*

but the mean runoff is larger than that estimated for the total land area on earth. It means that the areas where large rivers exist have comparatively high runoff rates.

Finally, the climatology of the global annual evaporation distribution is estimated (Fig. 6) through the water balance equation (3). Annual precipitation data used here are from Legates & Willmott (1990). Extremely high annual precipitation in the middle of the east Pacific ocean in the Legates' data cause the high annual evaporation in that area, and the locally concentrated high convergence along the Andes mountains in South America make the annual evaporation estimates negative. However, the distribution is generally realistic and acceptable.

To our knowledge, it is the first time that 4-dimensional assimilation global data have been used to estimate the world water balance, treating land and ocean separately and comparing in more than 30 large river basins.

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