*Hydrology of Warm Humid Regions* (Proceedings of the Yokohama Symposium, July 1993).
IAHS Publ. no. 216, 1993. 

# The water budget in the Amazon River basin during the FGGE period

**HIROSHI MATSUYAMA**
*Department of Geography, University of Tokyo, 7-3-1, Hongo, Bunkyo-Ku, Tokyo, 113, Japan*
**TAIKAN OKI**
*Institute of Industrial Science, University of Tokyo, 7-22-1, Roppongi, Minato-Ku, Tokyo, 106, Japan*
**KOOITI MASUDA**
*Department of Geography, Tokyo Metropolitan University, 1-1-1, Minami-Ōsawa, Hachiōji City, Tokyo, 192-03, Japan*

**Abstract** The seasonal change of the water budget in the Amazon River basin during the FGGE period is investigated, using the global objective analysed data set, precipitation data and discharge data. Some difference is found between the annual water vapour flux convergence and the annual runoff obtained by discharge data. This is due to the characteristics of the global objective analysed data set. The seasonal change pattern of precipitation shows good correspondence to that of water vapour flux convergence and monthly evapotranspiration remains almost constant within a year. The seasonal change of basin storage is very large and it is concluded that evapotranspiration in the entire basin is not affected by the seasonal change of basin storage even in the dry season. It is also found that the role of evapotranspiration on the water cycle in the basin is relatively more important in the dry season than in the rainy season.

## INTRODUCTION

It is very important to estimate the accurate value of evapotranspiration in a basin to investigate the water budget and water circulation in the basin. Especially, in the Amazon River basin, it is known that the annual evapotranspiration is about one half of the annual precipitation (e.g. Salati, 1987) and evapotranspiration contributes considerably to the local water circulation in the basin (Salati *et al.*, 1979). However, the seasonal change of the role of evapotranspiration on the water cycle in the basin and the relationship between evapotranspiration and basin storage has not yet been clarified. In this study, both of these problems are investigated during the FGGE period (the First GARP Global Experiment, from December 1978 to November 1979).

## DATA

### Precipitable water and water vapour flux convergence

The data used for the analysis of the atmospheric water budget is one of the FGGE "main" III-b data sets (hereafter called the FGGE III-b data) analysed at the European Centre for Medium-Range Weather Forecasts (ECMWF). The variables are wind vector, temperature, geopotential height of 15 levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 mb) and relative humidity of six levels (from 1000 mbars to 300 mbars) for each grid point with 1.875° intervals and it is analysed twice daily (0000 GMT and 1200 GMT).

The FGGE III-b data were analysed not only using real-time reports (24-h-after observations) but also with the late reports (3-months-after observations), and composed of the most dense observations ever available (Bengtsson *et al.*, 1982). It is thought to be one of the most reliable global objective analysed data sets though it has some problems (Masuda, 1988).

## Runoff

Runoff near the river mouth is calculated using the discharge data set of large rivers of the world prepared by the Global Runoff Data Centre (GRDC). In this data set, monthly river discharge of three stations in the Amazon River basin are included (Fig. 1) and they are estimated from the stage-discharge relationships (Meade *et al.*, 1979). The estimation error of discharge near the river mouth is probably about 10% (Nace, 1972).

In this study, summation of runoff at Altamira and Obidos, located near the mouth of the Xingu River and the Amazonas River respectively, is regarded as the total runoff of the Amazon River basin. The discharge data during the FGGE period is

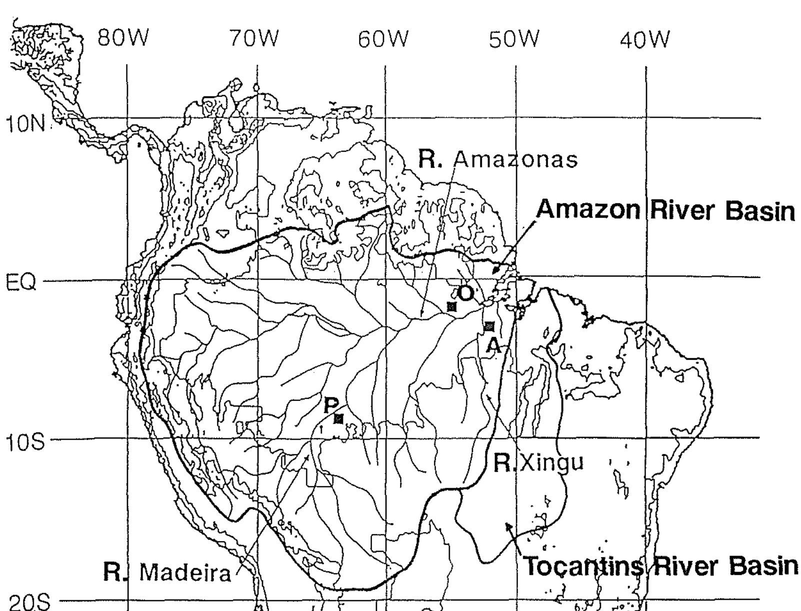


**Fig. 1** Map of the Amazon and Tocantins River basin showing the drainage network and river discharge stations in the Amazon basin (A: Altamira, O: Obidos, P: Porto Velho). Contour lines show 200, 1000 and 3000 m, respectively.

available in the case of Altamira, but for Obidos, the discharge data in 1979 are missing. Therefore the average runoff when discharge data are available (from 1928 to 1947, 1969, from 1971 to 1978, and from 1980 to 1983) is assumed to be the runoff at Obidos during the FGGE period. The coefficient of variation of the annual discharge at Obidos during the period of available data is about 8%.

## Precipitation

The areal precipitation during the FGGE period is calculated using the Monthly Climatic Data for the World published at the National Oceanic and Atmospheric Administration (NOAA). Its climatological value is also calculated using the World Monthly Surface Station Climatology compiled at the National Center for Atmospheric Research (NCAR). The daily precipitation data in Peru obtained from El Servicio Nacional de Meteorología e Hidrología (SENAMHI, the Hydrometeorological Agency of Peru) is also used for the calculation of the latter.

The areal precipitation is estimated using the Thiessen method (Thiessen, 1911) and there are 34 precipitation stations in the Amazon River basin during the FGGE period. The annual areal precipitation during the FGGE period and its climatological value are estimated to be 2152.6 and 2112.1 mm, respectively.

# METHOD

The atmospheric water balance equation and that of the basin are connected with the term $(E - P)$ and can be written as:

$$\frac{\mathrm{d}S}{\mathrm{d}t} + R_o = -(E-P) = -\nabla \cdot \boldsymbol{Q} - \frac{\mathrm{d}W}{\mathrm{d}t} \qquad (1)$$

where $S$, $R_o$, $E$, $P$ are basin storage, runoff near the river mouth, evapotranspiration, precipitation, respectively. $\nabla$ is the horizontal differential operator. $\boldsymbol{Q} = (Q_\lambda, Q_\phi)$ is the vertically integrated water vapour flux vector and each component indicates toward longitude and latitude, respectively. $W$ represents precipitable water.

Water vapour flux convergence is calculated using the central difference method to calculate the following equation, assuming that the earth is a sphere which has a radius of $\tau$:

$$-\nabla \cdot \boldsymbol{Q} = -\frac{1}{\tau \cos\phi} \times \left[ \frac{\partial Q_\lambda}{\partial \lambda} + \frac{\partial Q_\phi \cos\lambda}{\partial \phi} \right] \qquad (2)$$

Averaged in one year, the interannual variations of both precipitable water and basin storage are considered to be negligible in equation (1). Therefore the annual runoff and the annual water vapour flux convergence should be equal in the river basin.

In this study, the observed annual runoff are regarded as the real value and water vapour flux convergence is modified in order that its annual value should meet the annual runoff. Both monthly evapotranspiration in the entire basin and monthly change of basin storage are estimated by equation (1). The time scale of the analysis is one month because only monthly data can be obtained for the runoff.

## RESULTS

### Relationship between water vapour flux convergence and runoff

The seasonal changes of calculated water vapour flux convergence in the basin and estimated runoff near the river mouth are shown in Fig. 2. In the Amazon River basin during the FGGE period, the maximum of water vapour flux convergence appears in December and maximum runoff in May. The annual water vapour flux convergence and the annual runoff are estimated 737.3 and 1013.5 mm, respectively and the ratio of the latter to the former is 1.37. For comparison, the annual runoff values obtained by previous studies are shown in Table 1. They are estimated by the discharge data at Obidos or by the extrapolated discharge (e.g. Lvovich, 1973) near the river mouth. Except for Leopold (1962), all the annual runoff are more than 800 mm and their average is 977 mm.

Considering the estimation error of discharge near the river mouth, the coefficient of variation of discharge at Obidos and the comparison between the areal precipitation during the FGGE period and its climatological value, the annual water vapour flux convergence 737.3 mm is considered to be smaller than the annual runoff. Masuda (1988) suggested this is due to the characteristics of the FGGE III-b data analysed at the ECMWF. The annual runoff obtained by this study is similar to that of previous studies and it seems to be more precise and reliable than the annual water vapour flux convergence. Therefore, according to the fact that the annual water vapour flux convergence should meet the annual runoff, the former should be modified to meet the latter. Hereafter, the water vapour flux convergence multiplied by the factor 1.37 (abbreviated to modified water vapour flux convergence in the following) is used in the analysis of the water budget.

### The seasonal change of the water budget in the Amazon River basin

The seasonal changes of precipitation in the basin, modified water vapour flux

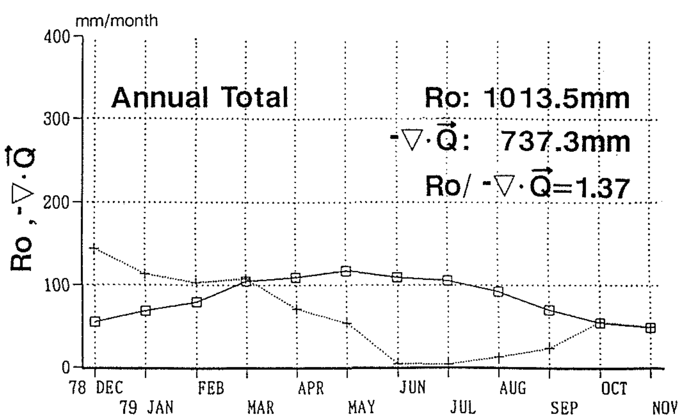


**Fig. 2** The seasonal changes of runoff near the river mouth and water vapour flux convergence in the basin. The annual value of water vapour flux convergence has not yet been adjusted to the annual runoff. □: runoff, +: water vapour flux convergence.

**Table 1** Drainage area, the annual discharge and runoff of the Amazon River.

| Reference | Site | Drainage area ($\times10^3$ km$^2$) | Discharge (m$^3$ s$^{-1}$) | Runoff (mm year$^{-1}$) | Period |
|---|---|---|---|---|---|
| Leopold (1962) | (M) | 5780 | 84 900 ~ 113 200 | 463 ~ 618 | |
| Henning (1970) | ($E$ + $T$) | 7180 | 190 000 | 835 | |
| Unesco (1971) | (O) | 4688 | 150 900 | 1015 | 1937-1946 |
| | (M) | 6300 | 203 000 | 1016 | 1937-1946 |
| Nace (1972) | (M) | 6300 | 175 000 | 876 | |
| UNESCO (1974) | (O) | 4688 | 173 000 | 1164 | 1972 |
| Baumgartner & Reichel | (O) | 5010 | 157 000 | 985 | |
| (1975) | (O) | 5000 | 157 000 | 990 | |
| Villa Nova *et al.* (1976)[a] | (M) | 6000 | 175 000 | 920 | |
| | (M) | 6150 | 199 700 | 1024 | 1971-1975 |
| Milliman & Meade (1983) | (O) | 4688 | 160 000 | 1076 | |
| Nishizawa & Koike (1992) | (M) | 6500 | 175 000 | 849 | |
| **This study:** | | | | | |
| Amazonas River | (O) | 4640 | 155 100 | 1054 | 1928-1947, 1969, 1971-1978, 1980-1983 |
| Xingu River | (A) | 450 | 8 400 | 591 | 1978.12-1979.11 |
| Total | (O + A) | 5090 | 163 500 | 1014 | |

(M) River mouth of the Amazon River basin, ($E$ + $T$): entire Amazon and Tocantins River basin (at these sites, discharge is not a direct observation but an extrapolated value)
(O): Obidos;
(A): Altamira;
(O + A): Obidos and Altamira.
Blanks in the period column indicate the period was not noted in each reference.
[a] Cited from Oltman (1967).

convergence and evapotranspiration are shown in Fig. 3. The seasonal change pattern of precipitation is in good agreement with that of modified water vapour flux convergence. From Fig. 3, monthly evapotranspiration in the entire basin is found to remain almost constant during the FGGE period. This does not contradict previous studies based on direct evapotranspiration measurements (e.g. Jordan & Heuveldop, 1981; Shuttleworth, 1988).

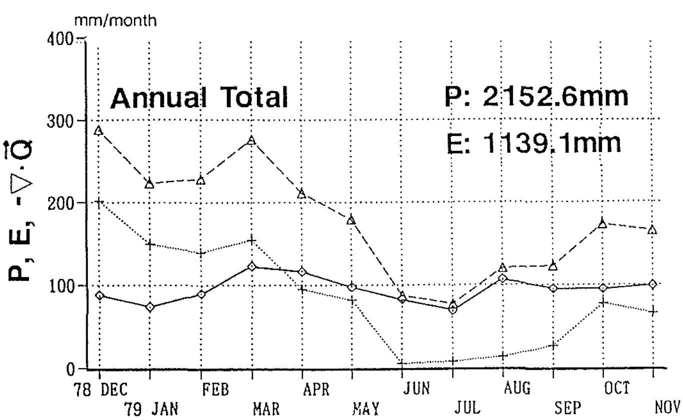


**Fig. 3** The seasonal changes of precipitation, modified water vapour flux convergence and evapotranspiration in the basin. △: precipitation, +: modified water vapour flux convergence, ◇: evapotranspiration.

The seasonal changes of evapotranspiration and the relative value of basin storage are shown in Fig. 4. Basin storage is modified so that the minimum value at the end of September should be zero. It is recognized that basin storage changes about 400 mm within a year.

Comparing Figs 2, 3 and 4, the following facts can be obtained. Precipitation during the rainy season does not run off immediately but is stored in the basin for some months and basin storage is at its maximum at the end of March. After that, basin storage begins to decrease and its maximum appears as that of runoff near the river mouth in May. Due to the storing effect of the precipitation during the rainy season in the basin, the seasonal change of monthly water vapour flux convergence does not agree with that of runoff in the Amazon River basin.

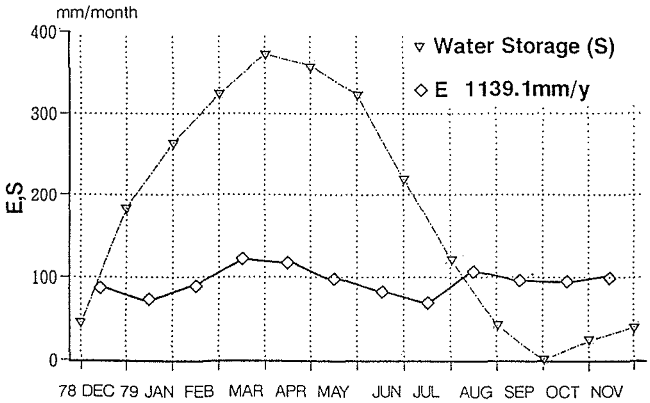


**Fig. 4** The seasonal changes of evapotranspiration and relative value of basin storage. Basin storage is modified in order that the minimum value at the end of September 1979 should be zero. ◇: evapotranspiration, ▽: relative value of basin storage.

## Relationship between evapotranspiration and basin storage

From Fig. 4, it is found that the seasonal change of basin storage is very large within a year, but evapotranspiration remains almost constant. From this fact, evapotranspiration in the Amazon River basin is not affected by the seasonal change of basin storage even in the dry season. Since evaporation from soil is neglected in the tropical rain forests (e.g. Villa Nova *et al.*, 1976; Jordan & Heuveldop, 1981) and almost the entire Amazon River basin is covered with tropical forests, this result indicates that the function of evapotranspiration of the tropical rain forests in the basin is very active regardless of the season. This is supported by Murai & Honda (1991), who show that the Normalized Difference Vegetation Index (NDVI, an indicator of the density of chlorophyll) of the tropical rainforests remains almost constant throughout the year.

## The role of evapotranspiration on the water cycle in the Amazon River basin

The seasonal change of evapotranspiration ratio is shown in Fig. 5. This is considered to show the seasonal difference of the role of evapotranspiration on the water cycle in

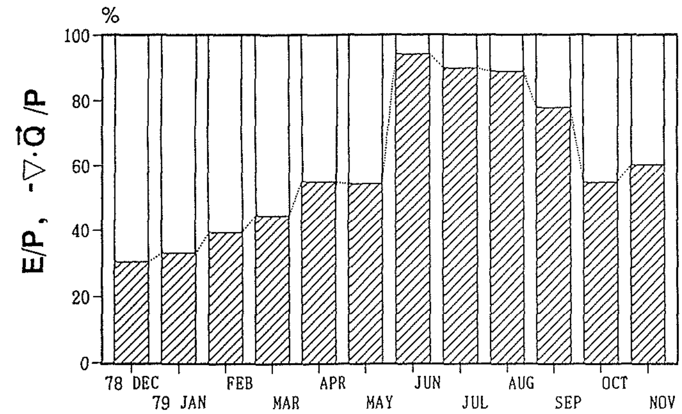


**Fig. 5** The seasonal change of evapotranspiration ratio in the Amazon River basin (hatched part). The balance is the ratio of water vapour flux convergence to precipitation.

the Amazon River basin. The annual precipitation and evapotranspiration in the Amazon River basin, estimated by this study, are 2152.6 and 1139.1 mm, respectively and this result is most similar to that of Baumgartner & Reichel (1975). The annual evapotranspiration ratio is about 53% and it does not contradict the results of previous studies (see Table 3 of Salati, 1987). However, its seasonal change is very large within a year.

In the rainy season, monthly evapotranspiration ratio is estimated to be about 30-40%, but in the dry season it is estimated much larger, that is, about 90%. Since water vapour flux convergence of the Amazon River basin becomes almost zero in the dry season (Fig. 2), evapotranspiration is almost equal to precipitation during this period. Therefore the role of evapotranspiration on the water cycle in the basin is relatively more important in the dry season than in the rainy season. However, the absolute value that evapotranspiration contributes to the water cycle in the basin is about 100 mm regardless of the season.

## CONCLUSION

The seasonal change of the water budget in the Amazon River basin during the FGGE period is investigated. The following results are obtained by this study:

- In comparison with water vapour flux convergence in the basin and runoff near the River mouth, the former is estimated to be smaller than the latter in this study.
- The seasonal change pattern of precipitation shows good correspondence to that of modified water vapour flux convergence and monthly evapotranspiration, calculated as the difference between them, is found to remain almost constant within a year.
- The seasonal change of the relative value of basin storage, estimated by the water balance equation of the basin, is found to be very large and evapotranspiration in the entire basin is not affected by the seasonal change of basin storage even in the dry season.

- The evapotranspiration ratio of the dry season is larger than that of the rainy season, and the role of evapotranspiration on the water cycle in the Amazon River basin is relatively more important in the dry season than in the rainy season.

**Acknowledgement** The authors thank Mr Alfonso Maguina Lopez, Director of SENAMHI for providing them with daily precipitation data in Peru.

## REFERENCES

Baumgartner, A. & Reichel, E. (1975) *The World Water Balance*. Elsevier, New York.

Bengtsson, L., Kanamitsu, M., Kållberg, P. & Uppala, S. (1982) FGGE 4-dimensional data assimilation at ECMWF. *Bull. Am. Met. Soc.* **63**, 29-43.

Henning, D. (1970) Anmerkung zum Abflußverhalten des Festlandes (Remarks on the runoff from continents) (in German with an English summary). *Met. Rdsch.* **23**, 91-92.

Jordan, C. F. & Heuveldop, J. (1981) The water budget of an Amazonian rain forest. *Acta Amazonica* **11**, 87-92.

Leopold, L. B. (1962) Rivers. *American Scientist* **50**, 511-537.

Lvovich, M. I. (1973) The global water balance. *EOS* **54**, 28-42.

Masuda, K. (1988) Problem notes about FGGE "main" IIIb datasets of ECMWF and GFDL (in Japanese). *Tenki* **35**, 5-19.

Meade, R. H., Nordin, C. F., Curtis, W. F. Jr, Rodrigues, F. M. C., do Vale, C. M. & Edmond, J. M. (1979) Sediment loads in the Amazon river. *Nature* **278**, 161-163.

Milliman, J. D. & Meade, R. H. (1983) World-wide delivery of river sediment to the oceans. *J. Geol.* **91**, 1-21.

Murai, S. & Honda, Y. (1991) World vegetation map from NOAA GVI data. In: *Applications of Remote Sensing in Asia and Oceania* (ed. by S. Murai), 3-6. Asian Association on Remote Sensing.

Nace, R. I. (1972) World hydrology: status and prospects. In: *World Water Balance* (Proc. Reading Symp., 1970), vol. I, 1-10. IAHS Publ. no. 92.

Nishizawa, T. & Koike, Y. (1992) *Amazon-Ecology and Development* (in Japanese). Iwanami, Tokyo.

Oltman, R. E. (1967) Reconnaissance investigations of the discharge and water quality Amazon. In: *Atas do Simpósio sobre a Biota Amazonica* **3**, (Limnologia), 163-185 (cited by Villa Nova *et al.*, 1976).

Salati, E. (1987) The forest and the hydrological cycle. In: *The Geophysiology of Amazonia* (ed. by R. E. Dickinson), 273-296. Wiley, New York.

Salati, E., Dall'Olio, A., Matsui, E. & Gat, J. R. (1979) Recycling of water in the Amazon basin: an isotopic study. *Wat. Resour. Res.* **15**, 1250-1258.

Shuttleworth, W. J. (1988) Evaporation from Amazonian rainforest. *Proc. Roy. Soc. Lond.* **B 233**, 321-346.

Thiessen, A. H. (1911) Precipitation averages for large areas. *Mon. Weath. Rev.* **39**, 1082-1084.

UNESCO (1971) *Discharge of Selected Rivers of the World*, vols 2-3. UNESCO, Paris.

UNESCO (1974) *Discharge of Selected Rivers of the World*, vols 3-2. UNESCO, Paris.

Villa Nova, N. A., Salati, E. & Matsui, E. (1976) Estimativa da evapotranspiração na bacia Amazônica (Estimation of evapotranspiration in Amazon basin)(in Portuguese with English summary). *Acta Amazonica* **6**, 215-228.