GAME's Contribution to GEWEX Water and Energy Balance Study

Kooiti Masuda*

(Frontier Research Center for Global Change / JAMSTEC)

*** Frontier Research Center for Global Change,**

3173-25, Showa, Kanazawa-ku, Yokohama 236-0001, Japan. e-mail: masuda@jamstec.go.jp

Abstract

Enhanced observations of GAME provide better data concerning the global energy and water cycle, especially over the Asian continent. Improvements achieved by utilizing GAME Reanalysis, operational rain gauge data and AAN, among others, are discussed.

Keyword: water balance, energy balance, GAME Reanalysis, operational rain gauge data, AAN

1. Water and Energy Balance Study

1.1. The rationale

To understand how the global energy and water cycle behaves, it seems a good way to look at variables appearing the equations of water balance and energy balance. These variables are well-defined in the context of the physical laws of conservation of mass and energy, and the values of them obtained at different space/time or by different approaches can be compared within the same framework in principle. The law of mass conservation does not guarantee the constancy of mass of water substance (water vapor, liquid water and ice combined), but, from the past experience, we know that contribution of chemical changes between water substance and other substance is relatively negligible. Water and energy balance study is, in its narrower sense, either to estimate one component of a balance equation that is not directly observed, or to assess the accuracy of our estimation when values for all components are somehow given. In its somewhat broader sense, it also means to recognize the actual magnitude and the relative importance of each term in the equations, and how they vary across the wide range of space and time.

Water and energy balance study in the global scale is possible only with global scale data sets. Studies in the smaller spatial scales than global are, however, also important to it. Global data sets inevitably depend on indirect estimation, either by remote sensing or by numerical modeling. Regional studies can utilize more direct observations, and thus make the quality of evaluation of global scale balance better. Even spatially and temporally limited experimental observations can be compared with global data sets and give suggestions about possible improvement of global data sets.

Regional studies also contribute to understanding of the global energy and water cycle by way of inter-regional comparison. Even people who study something global usually live in a limited region, and characteristics of climate and hydrology of the region strongly influence their view of the world. We should know how similar and how different they are in other regions of the world. In this context it is again important that they are expressed in the same framework. Attention to variables entering the balance equations is a good point to start.

1.2. GEWEX Water and Energy Balance Study

Water and Energy Balance Study (WEBS) in the context of Global Energy and Water Cycle Experiment (GEWEX) was proposed as a concrete study item by John Roads (the present chairperson of GEWEX Hydrometeorological Panel (GHP), based at Scripps Institute of Oceanography, USA) (see `http://ecpc.ucsd.edu/ghp/WEBS.html`). It is one of the attempts synthesize the findings of GEWEX continental-scale experiments (CSEs). GAME is one of the CSEs.

Roads had played an important role in the synthesis of water and energy balance obtained during the GEWEX Continental-scale International Project (GCIP) conducted in the Mississippi river basin. He edited a CD-ROM for GCIP WEBS (Roads et al. 2002a), including water and energy balance products both global-scale and regional-scale, and both observational and model-derived. He participated in comparative studies for GCIP (e.g. Maurer et al. 2001). On the other hand, he also discussed water and energy balance of all CSE regions with global data only (Roads, 2002, Roads et al., 2002b).

In 2002, a working group for WEBS was organized under GHP with Roads's initiative, and I became its member representing GAME. The practical goal of the project is to make an inter-regional comparison of water and energy balance, similar to Roads et al. (2002b), but with regional data sets from CSEs in addition to a common set of global data.

The target of this limited part of WEBS is the aspects of water and energy balance that can be expressed by monthly averages. The horizontal resolution is not explicitly specified, but it is implicitly determined from the characteristics of global data sets. Their horizontal resolution is nominally between 1.0 degree and 2.5 degrees latitude/longitude, and some variables such as moisture convergence C (see below) have actually coarser resolution than nominal. The variables to be assembled and discussed is also limited to those appearing in the vertically integrated water and energy balance equations. The equations can be written as follows in my version of notation. Some of them are not exact but approximate.

- Mass balance of water on an area of land (preferably a river catchment)

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P - E - R \tag{1}$$

- Mass balance of water vapor in an atmospheric column

$$\frac{\mathrm{d}W}{\mathrm{d}t} = E - P + C \tag{2}$$

- Energy balance at the surface

$$G = R_{\mathrm{net,sfc}} - H - LE \tag{3}$$

- Total energy balance in an atmospheric column

$$\frac{\mathrm{d}(e_{\mathrm{d}} + LW)}{\mathrm{d}t} = R_{\mathrm{net,top}} - G + (C_{\mathrm{d}} + LC) \tag{4}$$

- "Dry" energy balance in an atmospheric column

$$\frac{\mathrm{d}e_{\mathrm{d}}}{\mathrm{d}t} = R_{\mathrm{net,top}} - R_{\mathrm{net,sfc}} + H + LP + C_{\mathrm{d}} \tag{5}$$

where S is terrestrial water storage, W is water vapor content in the atmosphere, P is precipitation, E is evaporation from surface, R is runoff, C is convergence of horizontal transport of water vapor in the atmosphere, e_{d} is "dry" energy content in the atmosphere, $R_{\mathrm{net,top}}$ is net downward radiation at the top of the atmosphere, $R_{\mathrm{net,sfc}}$ is net downward radiation at the surface, G is net downward energy flux at the surface (conduction below land surface), H is net upward sensible heat flux at the surface, C_{d} is convergence of horizontal transport of "dry" energy in the atmosphere, and L is latent heat of vaporization of unit mass of water.

Obviously, this limited target does not fully represent the synthesis of activities of CSEs such as GAME. There are many field campaigns, however intensive, which do not cover one calendar month and thus cannot contribute numerical values to the intercomparison. There are many studies that aim at three-dimensional distribution of heat sources in the atmosphere. One of such framework was "Q_1 and Q_2" first formulated by Yanai (1961) and applied in the context of GAME by Ueda et al. (2003) among others. The vertically integrated monthly statistics is just the first step of WEBS, or "Initiative 1" as called by Masuda and Sohn (2003).

2. Atmospheric reanalyses

2.1 Introduction

Data assimilation has become familiar in the context of meteorology and increasingly also of oceanography and hydrology. A rough description of it is to run a forecast model (in a computer), continuously updating the forecast variables with observational data, to achieve gapless gridpoint values which are good approximation of the real world and physically consistent. Actually the insertion of data may be intermittent rather than continuous, and consistency of the values in the products is not ideal. Assimilation of meteorological data is routinely done in real-time as a part of numerical weather prediction. They can incorporate experimental observations if they are reported in a standardized way in time. Actually, some of enhanced radiosonde observations in GAME were used this way. But most of experimental observations become available many days later. To utilize them, data assimilation should be done in non-real-time manner.

Non-real-time assimilation projects or their products are often called "reanalyses". Some of reanalyses covers many decades. U.S. National Centers for Environmental Prediction (NCEP) as well as European Centre for Medium-range Weather Forecasts (ECMWF) have issued long-term reanalysis data sets. These data sets comprise a major part of "global data sets" utilized in global WEBS together with global synthesis based on satellite observations. Also, Japan Meteorological Agency (JMA) and Central Research Institute of Electric Power Industries (CRIEPI) jointly conduct a project "JRA" (see `http://www.jreap.org/`) to produce global reanalysis covering a period from 1979 to present. Later versions of intercomparison of global WEBS will include JRA.

2.2 GAME Reanalysis

In GAME, two versions (1.1 and 1.5) of "GAME Reanalysis"(GAME-RA) was produced by a team based at Meteorological Research Institute of JMA (Yamazaki et al. 2003). (There will be no more product in this series because the team is reorganized as a part of the JRA team.) These are global reanalyses that cover a 7-month period from April to October 1998. The horizontal resolution is "T213" and its grid interval is about 5.6 degrees latitude/longitude. It used a somewhat modified version of JMA's operational data assimilation system. The scheme for spatial interpolation is "optimal interpolation (OI)". It was planned to implement "three-dimensional variational method (3D-VAR)" in the Version 2. But it was not successful to produce better results by 3D-VAR than by OI. Thus a revised version with OI is released as Version 1.5 instead of planned Version 2. (Later, after more research work, 3D-VAR was implemented in JMA's operational data assimilation and it is also used in JRA.) The main difference between GAME-RA and JMA operational global analysis is the richness of input data. The period of Reanalysis covers the Intensive Observing Period of GAME-Tropics, GAME-Tibet, GAME-HUBEX and also SCSMEX (South China Sea Monsoon Experiment), TIPEX (Tibetan Plateau Experiment) and KORMEX (Korean Monsoon Experiment), and many experimental data are contributed in addition to operational data transmission.

As I compared water balance of GAME-RA with other global data sets (Masuda, 2003), it is found that monthly mean, continental scale precipitation as derived from the forecast model of the reanalysis was close to observation-based data such as Global Precipitation Climatology Project (GPCP) in cold region in summer where both of the two versions of NCEP-RA give excessive precipitation. On the other hand, the balance of atmospheric water vapor between P, E and C that should vanish, is worse in GAME-RA than in NCEP-RA. Comparison of evaporation with observations (though they are local and not necessarily representative of regional averages) suggests that forecast models of both GAME-RA and NCEP-RA over-estimates evaporation. In the tropics, agreement of precipitation between GAME-RA and observation-based data is good in some region and not so good elsewhere. It is noteworthy that the regional average precipitation in the Indochina Peninsula is represented well, presumably due to enhanced data of GAME-Tropics. Distribution of precipitation within this region is not so well reproduced, however.

GAME-RA is used in many studies related to water and energy balance. Noteworthy examples are three-dimensional heat and moisture budgets around the Ti-

betan Plateau (Ueda et al. 2003) and transports of water isotopes around the GAME-Tropics region (Yoshimura et al., 2003). It is also used as boundary and initial conditions for studies by using regional meteorological models.

2.3 Other atmospheric reanalysis activities in GAME

GAME-HUBEX Regional Reanalysis (Wakatsuki et al. 2003) was produced by using JMA's Regional Spectral Model (RSM) data assimilation system with input enhanced by experimental observations of HUBEX. It covers a one month time frame from 19 June to 19 July 1998, at 6 hour time interval and 20 km spatial resolution. GAME-RA Version 1.1 was used as boundary and initial conditions.

Tanaka et al. (2004) combine JMA's RSM data assimilation system with a land surface model "SiBUC", and try to produce an improved reanalysis of the coupled land-atmosphere system.

3. Collection of operational data

3.1. Collection of precipitation data

In addition to experimental observations, agencies in many countries contributed data of their operational observations to GAME. The coverage is uneven, due partly to policies of the agencies and partly to interests of the scientists who collected the data.

Among them, the collection of daily precipitation data in Southeast Asian countries is noteworthy. It is achieved by continuous collaborations between Southeast Asian countries (especially Thailand) and Japan, enthutiastic data collection by Jun Matsumoto (Univ. Tokyo), and data management by Yasushi Agata (Univ. Tokyo) at `http://hydro.iis.u-tokyo.ac.jp/GAME-T/GAIN-T/`.

3.2. Impact of precipitation data

Utilizing this GAME-T collection together with other sources (notably the collection by the Mekong River Commission, an international organization based now at Vientiane), Masuda et al. (2004) analyzed the spatial distribution and the seasonal cycle of precipitation in Indochina Peninsula. It is found that the contrast between maxima in mountainous areas and minima in lowlands is larger than global data sets suggest. It is still difficult for global forecast models to simulate the pattern of precipitation in this area. The problem of observation-based global data sets is that few reports from such countries as Myanmar, Laos and Cambodia arrive at meteorological agencies in Europe or North America where the global archive is compiled. It happened, however, that the regional average precipitation in the middle Mekong river basin (between Chiang Saen [Thailand] and Pakse [Laos]) is almost the same whether observation-based global data sets such as GPCP or the enhanced rain gauge data are used. In the upper Irrawaddy (above Sagaing [Myanmar]) the difference is significant, though comparison with river discharge suggests that precipitation in this region is still under-estimated with the enhanced rain gauge data.

4. Regional land surface fluxes

4.1. Asian AWS Network

In GAME, automated weather stations were installed in many locations on the Asian continent to continuously monitor surface energy balance components and related variables. Many of them are collectively called Asian AWS Network (AAN) with the arrangement of Michiaki Sugita et al. at the University of Tsukuba (`http://www.suiri.tsukuba.ac.jp/Project/aan/aan.html`). Data of hourly or half-hourly observations are available both on CD-ROMs and on the Internet. Surface fluxes observed by AAN was used for evaluating the fluxes calculated by the forecast model of GAME-RA (Yatagai et al. 2003).

4.2. Comparison between AAN and satellite retrievals

AAN data is also useful for evaluating radiative fluxes at the surface obtained by retrievals of satellite observations. For this purpose, more precise observations are desirable. In Asia, however, stations of Baseline Surface Radiation Network do not except except in Western Asia and Japan. Several precision radiation stations were installed by GAME-Radiation activity and some of them continues as part of SKYNET, but, because of difficulty in maintaining precision instruments on the field, their records are generally less continuous than AAN.

On the side of satellite retrievals, the Surface Radiation Budget (SRB) data set produced by Paul Stackhouse et al. at NASA Langley Research Center (LaRC, see `http://srb-swlw.larc.nasa.gov/GEWEX_SRB_homepage.html`) is designated as the GEWEX SRB product, but its coverage is July 1983 to October 1995 as has been released and do not overlap the Intensive Observing Periods of GAME. The production of SRB uses cloud information from the "D series" of International Satellite Cloud Climatology Project (ISCCP). Zhang and Rossow at NASA Goddard Institute of Space Studies (GISS) who produced ISCCP data has also made a data set (called "FD") of radiative fluxes which extends to June 2001 `http://isccp.giss.nasa.gov/projects/flux.html`. Rachel Pinker et al. at the University of Maryland also made "Pathfinder" shortwave flux data which extends to December 1998 (`http://www.atmos.umd.edu/~srb/pathfinder/`). The FD and Pathfinder data sets have lower spatial resolutions (2.5 deg. lat./long.) than LaRC SRB (1 deg.), however.

Masuda (2004) compared monthly mean values of downward shortwave and longwave fluxes at several AAN stations with those of the nearest grid boxes of SRB, FD and Pathfinder data sets. Interpretation of the difference found is difficult, especially in the tropics where there seems to be significant regional inhomogeneity of cloud distribution. In some cases, however, the comparisons reveal systematic problems of satellite retrievals. Downward shortwave radiation as given by SRB and Pathfinder, which use the same Pinker-Laszlo algorithm, are underestimates in the Tibetan Plateau. It seems that the high land elevation and consequently thin atmospheric column are not properly taken into account in the productions. FD over-estimates downward longwave radiation in Siberia in winter and perhaps under-estimates it in Tibet in summer. It can be traced back to the differ-

ence between the actual atmospheric temperature profile based on TOVS retrievals which was used in the production of FD. SRB does not share this bias because LaRC used temperature profile from an atmospheric reanalysis (GEOS by NASA), which is likely to better represent realistic vertical profile than TOVS retrievals.

4.3. Evaluation of regional land surface fluxes

One way to know surface energy and water fluxes in the regional scale is running a land surface model with near-surface meteorological data as input.

For the HUBEX region, Tanaka et al. (2001) run SiBUC on a 5 minute latitude/longitude (approximately 10 km) grid for May to August 1998. Among the input meteorological data, downward radiation was estimated by using Geostationary Meteorological Satellite observations. Their team continues improvement of the assimilation.

For the Tibetan Plateau, Xu and Haginoya (2001) and Xu et al. (2004) use a simple model of energy and water transfer in the soil layer (assuming that the effect of vegetation is negligible) and operational meteorological data to obtain surface fluxes at the operational stations in the plateau for 1997 and 1998. The empirical formula used in the study was calibrated with reference to experimental observations. Also, the groups lead by Toshio Koike at the University of Tokyo, Yaoming Ma at Institute of Tibetan Plateau Research, and Hirohiko Ishikawa at Kyoto University utilize satellite data and land surface models.

5. Concluding remarks

I am afraid I have missed many studies relevant to this subject. I welcome information about them.

Even though research funding under the name of GAME is about to end, utilization of the rich information obtained by GAME has just started. Interpretation of it requires more thinking, more comparison, or maybe modelling studies. We should continue water and energy balance studies and merge our experience of GAME into a broader knowledge base.

References

Masuda, K., Evaluation of precipitation of GAME Reanalysis on continents (in Japanese). *Proc. 2003 Spring Meeting of Meteorol. Soc. Japan*, No. P467, 2003. (English version at `http://www.jamstec.go.jp/frcgc/research/p2/masuda/gamerean/masuda2003/index.html`).

Masuda, K., Surface radiation budget: comparison between global satellite-derived products and land-based observations in Asia and Oceania. Paper presented at International Radiation Symposium 2004, Busan, Korea, 2004. (See `http://www.jamstec.go.jp/frcgc/research/p2/masuda/radcmp/index.html`).

Masuda, K., J. Matsumoto, Y. Agata, B. Ailikun and T. Yasunari, Precipitation climatology of continental Southeast Asia. (English version to be linked under `http://www.jamstec.go.jp/frcgc/research/p2/masuda/index.html`). *Proc. 2004 Autumn Meeting of Meteorol. Soc. Japan*, No. A359, 2004.

Masuda, K. and B.J. Sohn, GAME Water and Energy Balance Study. *GAME Letter*, No. 5, 8-13, 2003. (or see Masuda's draft at `http://www.jamstec.go.jp/frcgc/p2/masuda/gamewebs/200306.html`).

Maurer, E.P., G.M. O'Donnell, D.P. Lettenmaier and J.O. Roads, Evaluation of the land surface water budget in NCEP/NCAR and NCEP/DOE Reanalyses using an off-line hydrologic model. *J. Geophys. Res.*, **106**, 17841-17862. 2001.

Roads, J., Closing the Water Cycle. *GEWEX News*, **12**, No. 1, 1 and 6-8, 2002.

Roads, J. et al. eds., *GEWEX Continental-scale International Project (GCIP) Water and Energy Budget Synthesis (WEBS) 1996-1999*. CD-ROM. 2002a. (See `http://ecpc.ucsd.edu/gcip/gcipwebs.html`).

Roads, J., M. Kanamitsu and R. Stewart, CSE water and energy budgets in the NCEP-DOE Reanalysis II. *J. Hydrometeorol.*, **3**, 227 - 248, 2002b.

Tanaka, K., O. Kozan, T. Nakamura, M. Shiiba and S. Ikebuchi, Land data assimilation in the GAME-HUBEX. *5th Int'l Study Conference on GEWEX in Asia and GAME*, 697 - 702, 2001.

Tanaka, K., K. Souma, K. Tsuboki and S. Ikebuchi, Production of final dataset of GAME-HUBEX Regional 4DDA by JSM-SiBUC. This symposium, 2004.

Ueda, H., H. Kamahori and N. Yamazaki, Seasonal contrasting features of heat and moisture budgets between the eastern and western Tibetan Plateau during the GAME IOP. *J. Climate*, **16**, 2309 - 2324, 2003.

Wakatsuki, Y., K. Tsuboki, T. Kawahata and H. Nakamura, Production of GAME/HUBEX Regional Reanalysis data set (in Japanese). *Proc. 2003 Spring Meeting of Meteorol. Soc. Japan*, No. P428, 2003.

Xu, J.and Haginoya, S., An estimation of heat and water balances in the Tibetan Plateau. *J. Meteorol. Soc. Japan*, **79**, 485 - 504, 2001.

Xu, J., Haginoya, S., Masuda, K. and Suzuki, R., An estimation of heat and water balances in the Tibetan Plateau in 1997 - 1998. Submitted to *J. Meteorol. Soc. Japan*, also in this symposium, 2004.

Yamazaki, N., K. Takahashi and A. Yatagai, Report on the GAME Reanalysis. *GAME Phase 1 Summary Reports* (GAME Publ. No. 37), 81 - 87, 2003. (See also `http://gain-hub.mri-jma.go.jp/GAME_reanal.html`).

Yanai, M., A detailed analysis of typhoon formation. *J. Meteorol. Soc. Japan*, **39**, 187 - 214, 1961.

Yatagai, A., M. Sugita, N. Yamazaki, M. Oh'izumi, A comparative study of the surface fluxes derived from meteorological four dimensional data assimilation products (GAME Reanalysis) with Asian Automatic Weather Station Network (AAN) observations over the Tibetan Plateau. *Proc. APHW2003*, Asia Pacific Association of Hydrology and Water Resources, 722 - 727, 2003.

Yoshimura, K., T. Oki, N. Ohte, and S. Kanae, A quantitative analysis of short-term ^{18}O variability with a Rayleigh-type isotope circulation model. *J. Geophys. Res.*, **108**, 4647, doi:10.1029/2003JD003477, 2003.