

EVALUATION OF FRESHWATER FLUX OVER THE OCEAN

M. Kubota, T. Watabe, S. Iwasaki

School of Marine Science and Technology, Tokai University, 3-20-1, Orido, Shimizu, Shizuoka, Shizuoka, JAPAN
424-8610 - (Kubota,watabe,iwasaki)@mercury.oi.u-tokai.ac.jp

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ABSTRACT:

Huge amounts of evaporation and precipitation exist over the ocean and play an important role in the global climate system. Therefore, evaluation of freshwater flux is critical for understanding the mechanism of global climate change. Recently we can use three kinds of global freshwater flux products such as in situ data, satellite data and reanalysis data. Although various studies were carried out using those data, it is difficult to determine which data is most accurate because we don't know the true value for global freshwater flux. One of important thing is to clarify the differences among those data and the cause of the differences. For this purpose we compare various freshwater flux products over the ocean in this study. We use GSSTF2, HOAPS3, and J-OFURO2 evaporation products and GPCP2, CMAP and HOAPS3 precipitation products as satellite-based products. OAF flux evaporation product that is hybrid data is also used here. On the other hand, we use ERA40, NRA1, and NRA2. We assume a reference freshwater flux product to be J-OFURO2-GPCP2. Temporal and spatial resolutions are one month and $1^{\circ} \times 1^{\circ}$ degree, respectively. The analysis period is 1988-2000. Reanalysis products generally tend to overestimate freshwater flux from the ocean to the atmosphere in the mid-latitudes and underestimate in the low-latitudes. We estimated integrated freshwater flux over the ocean. If we use reanalysis products, the integrated value is considerably large compared with that of the reference data. Moreover, if we use a reanalysis product for precipitation and another product for evaporation, we obtain a negative freshwater flux that means freshwater flux from the ocean to the atmosphere. We investigated the trend of integrated freshwater flux. For reference data integrated freshwater flux shows positive trend that means freshwater flux from the ocean to the atmosphere increases as time goes on. On the other hand, if we use reanalysis products, integrated freshwater flux shows negative trend that means freshwater flux from the atmosphere to the ocean.

1. INTRODUCTION

The global hydrological cycle, which consists of many components, is an important issue from not only scientific but also social viewpoints, related to the earth environmental problem. In particular, evaporation (E) and precipitation (P) over the ocean are very large compared with other components. Therefore, the accurate estimation and the continuous monitoring are critical for understanding the global hydrological cycle. For these objectives we can use both of satellite-derived and reanalysis products at present. However, there are not so many studies related to this issue. Mehta et al. (2005) studied the average annual cycle of the atmospheric branch of the fundamental global water cycle. They found that 75% to 85% of the total global evaporation and approximately 70% of the total global precipitation occur over the ocean in each season. Also Schlosser and Houser (2007) assessed the capability of a global data compilation, largely satellite-based, to depict the global atmospheric water cycle's mean state and variability by using various data. They pointed out that the mean annual cycle of global E-P can be up to 5 times larger to that of total precipitable water, depending on the choice of ocean evaporation data and the ocean evaporation trends are driven by trends in SSMI-retrieved near-surface atmospheric humidity and wind speed, and the largest year-to-year changes are coincident with transitions in Special Sensor Microwave Imager (SSM/I) fleet. However, both of Mehta et al. (2005) and Schlosser and Houser (2007) did not use reanalysis products in their studies. In this study we carry out intercomparison of global freshwater flux (FWF) products over the ocean, including both of satellite-derived and reanalysis products. Moreover, the differences among various products, global budget by each freshwater

product and trend of evaporation, precipitation and freshwater flux are analyzed.

2. DATA

We use various kinds of products. Some of products provide precipitation or evaporation only. On the other hand, some of products provide both of precipitation and evaporation. The Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations Version 2 (J-OFURO2) (Kubota and Tomita, 2007), The new version of the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data set 3 (HOAPS3) (Andersson et al., 2007), Goddard Satellite-Based Surface Turbulent Fluxes Version 2 (GSSTF2) (Chou et al., 2003) and Objectively analyzed Air-sea heat Fluxes (OAF flux) (Yu et al., 2004, Yu et al., 2008) are used as evaporation data. The first three products are satellite data and the OAF flux is a hybrid product and made by merging satellite data, reanalysis data and in situ data. Also we use Global Precipitation Climatology Project Version 2 (GPCP2) (Adler et al., 2003), Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1997) and HOAPS3 precipitation data. HOAPS3 use only satellite data, but GPCP2 and CMAP use not only satellite data but also in situ data. Moreover, we use reanalysis product such as the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research reanalysis (NRA1) (Kalnay et al., 1996), NCEP/Department of Energy reanalysis (NRA2) (Kanamitsu et al., 2000), European Centre for Medium-Range Weather Forecast (ECMWF) Reanalysis (ERA40) (Gibson et al., 1999, Simmons and Gibson, 2000) and Japan Re-Analysis 25 year

(JRA25) (Onogi et al., 2007). All of these products include precipitation and evaporation data.

The description of each product is given in Table 1. As shown in the table, data period and temporal and spatial resolutions are different depending on each product. Therefore, we unify temporal and spatial resolutions and analysis period. The temporal and spatial resolutions are monthly and 1°x1°, respectively. The analysis period is from 1988 to 2000.

We don't know which global freshwater product is more accurate. Therefore, we assume combination of J-OFURO2 and GPCP2 to be a reference freshwater flux product in this study.

Table.1 Description of each product.

Data Set	J-OFURO2	HOAPS3
Period	1988/1-2006/12	1987/7-2005/12
Spatial resolution	1°	1°
Temporal resolution	Daily	12 hours
Data Set	GSSTF2	OAFflux
Period	1987/7-2000/12	1958/1-2008/12
Spatial resolution	1°	1°
Temporal resolution	Daily	Daily

- Japanese-Ocean Flux data sets with Use of Remote sensing Observations Version 2 (J-OFURO2)
- Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data 3 (HOAPS3)
- Goddard Satellite-Based Surface Turbulent Fluxes 2 (GSSTF2)
- Objective Analyzed Air-Sea Fluxes (OAFflux)

Data Set	GPCP2	CMAP	HOAPS3
Period	1979/1-present	1979/1-2008/7	1987/7-2005/12
Spatial resolution	2.5°	1°	1°
Temporal resolution	Daily	12 hours	12 hours

Data Set	NRA1	NRA2	ERA40	JRA25
Period	1948/1-present	1979/1-present	1967/9-2002/8	1979/7-present
Spatial resolution	Gaussian grid T62 (180km)	Gaussian grid T62 (180km)	Gaussian grid TL159 (110km)	Gaussian grid T106 (110km)
Temporal resolution	6 hours	6 hours	6 hours	6 hours

- The Global Precipitation Climatology Project Version.2 (GPCP2)
- Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP)
- NCEP/NCAR Re-analysis (NRA1)
- NCEP-DOE Re-analysis (NRA2)
- ECMWF Re-analysis 40 (ERA40)
- Japanese Re-analysis 25 (JRA25)

3. INTERCOMPARISON

Figure 1 shows average freshwater flux field derived from J-OFURO2 evaporation and GPCP2 precipitation. Positive values mean freshwater transfer from the ocean to the atmosphere. We can see general feature about freshwater flux over the ocean. For example, large freshwater transfer from the atmosphere to the ocean exists in the tropical regions corresponding to ITCZ and SPCZ. On the other hand, we can see large freshwater transfer from the ocean to the atmosphere in the mid-latitudes, so-called ocean desert.

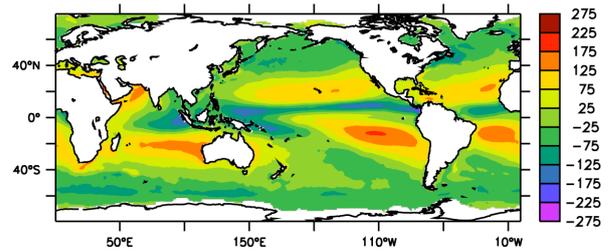


Figure 1. Average field for the reference freshwater product (GPCP2-J-OFURO2) (unit: mm/month).

Figure 2 shows average difference fields between reference product and other products. Both of GSSTF2-CMAP or OAFflux-CMAP products overestimate in the high-latitudes and underestimate in the tropical regions. Such differences mainly depend on the differences of precipitation data. The differences for HOAPS3 are relatively small. However, those for all reanalysis products are considerably large. All reanalysis products overestimate in the mid- and high-latitudes and underestimate in the tropical regions. In particular ERA40 extremely overestimates in the mid-latitudes and both of NRA products underestimate in the tropical regions. We will analyze the reason of the differences between the reference product and

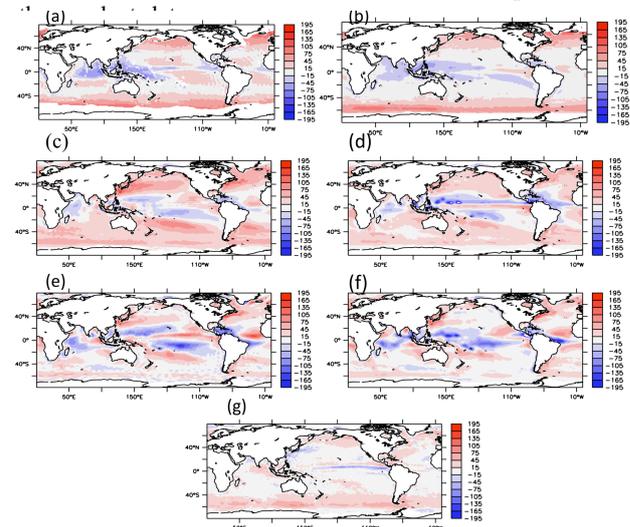


Figure 2. Average difference (mm/month) between the reference product and (a) GSSTF2-CMAP2, (b) OAFflux-CMAP, (c) ERA40, (d) JRA25, (e) NRA1, (f) NRA2, and (g) HOAPS3.

Figure 3 shows meridional profiles of freshwater flux. Horizontal axis means a monthly-accumulated value. Positive values mean freshwater flux from the ocean to the atmosphere. General features are in common. We can see large transfer from the atmosphere to the ocean around 10°N corresponding to ITCZ, and larger

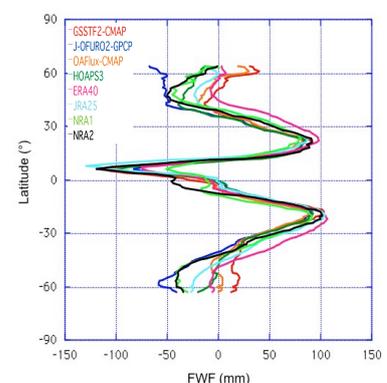


Figure 3. Meridional Profile of average freshwater flux.

transfer from the ocean to the atmosphere around 25° in both hemispheres. However, the quantitative differences are not negligible. For example, the difference between the maximum value JAR25 and the minimum value HOAPS reaches to more than 50 mm. Moreover, the scatter is considerably large in the high-latitudes. Most products show negative transfer that is freshwater transfer from the atmosphere to the ocean in the high-latitudes. However, ERA40 and OAFflux-GPCP2 show positive flux there.

4. ANALYSIS OF DISCREPANCIES BETWEEN VARIOUS PRODUCTS

We analyze discrepancies of freshwater flux among various products in terms of precipitation and bulk variable related to evaporation following to Bourras (2006). dFWF is the differences between the reference product and other products.

$$dFWF = dP * (-1) + \frac{\partial E}{\partial U_a} dU_a + \frac{\partial E}{\partial Q_a} dQ_a + \frac{\partial E}{\partial Q_s} dQ_s$$

$$\frac{\partial E}{\partial U_a} = L\rho_a C_E (Q_s - Q_a), \frac{\partial E}{\partial Q_a} = -L\rho_a C_E U_a, \frac{\partial E}{\partial Q_s} = L\rho_a C_E U_a$$

$dP = P(Other) - P(GPCP2)$
 $dU_a = U_a(Other) - U_a(J-OFURO2)$
 $dQ_a = Q_a(Other) - Q_a(J-OFURO2)$
 $dQ_s = Q_s(Other) - Q_s(J-OFURO2)$
 $dFWF = FWF(Other) - FWF(J-OFURO2 - GPCP2)$
 where U_a :wind speed, Q_a :specific humidity, Q_s :saturated specific humidity. All terms in the right hand side are the contribution of each parameter to the deviation between reference product and other products. Figure 4 shows map of the differences between the reference product (J-OFURO2-GPCP2) as shown before and other products and the contribution of each parameter. For example, we can see underestimation in the western Pacific and overestimation in the high-latitudes in the difference between the reference product and the combination of GSSTF2 and CMAP. On the other hand, we can see the similar feature in the difference between CMAP and reference product, that is GPCP2. Also the contribution by Wind and Q_s is small and by Q_a is large. Therefore, we can conclude the differences in this case are mainly caused by precipitation and Q_a and the distribution pattern is determined by precipitation. Basically the contributions by wind speed and Q_s are relatively small, while those by precipitation and Q_a are critical. Also it is interesting that the contribution of CMAP precipitation is larger than that of HOAPS3 precipitation. HOAPS3 Q_s contributes to underestimation and Q_a contributes overestimation in the same regions. As a result, the differences between HOAPS3 and the reference product are considerably small as shown in this figure.

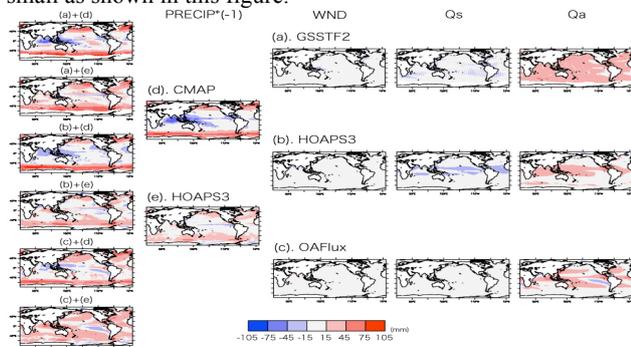


Figure 4. Contributions to the deviation between J-OFURO2-GPCP2 freshwater flux and other freshwater products.

Figure 5 shows similar figures except for reanalysis products. All products underestimate freshwater flux in the tropical

regions as mentioned before because they overestimate precipitation in these regions. It is interesting that not only precipitation but also other parameters contribute to the differences. Wind speed and Q_a contribute to the underestimation, and Q_s contributes to the weak overestimation.

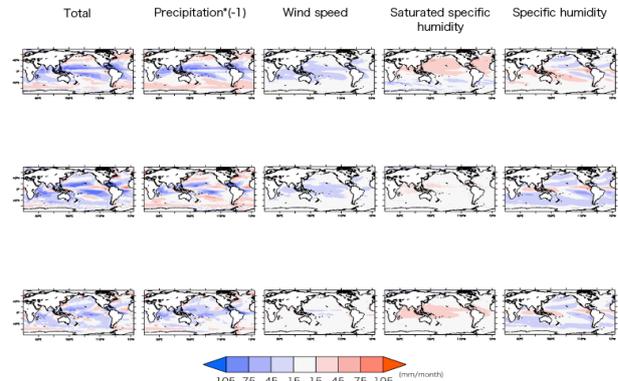


Figure 5. Contributions to the deviation between J-OFURO2-GPCP2 freshwater flux and other freshwater reanalysis products. Upper: JRA25, Middle: NRA1, Lower: NRA2.

5. GLOBAL BUDGET

We also investigate global budget of evaporation, precipitation and freshwater flux over the ocean. Figure 7 shows our analysis region. We exclude GSSTF2 product from our analysis because there are many vacant data in this product.

Table 2 gives global budget for evaporation. As mentioned before, reanalysis products except ERA40 show larger values compared with other products including previous results. The minimum and the maximum are given by J-OFURO2 and NRA2, respectively. Table 3 gives global budget for precipitation. The minimum and the maximum are given by HOAPS3 and ERA40, respectively. However, the differences between each product are small compared with evaporation.

Table 4 gives global budget for freshwater flux. If we use reanalysis product for evaporation, we obtain the extremely large freshwater flux from the ocean to the atmosphere. Also if we use ERA40 or NRA2 precipitation, we obtain negative values. Since negative values mean river carry water from the ocean to the land, the results seem to be unreal. It is surprising that the global budget is considerably divergent, in particular reanalysis product shows very large values.

Table 2. Global average evaporation (10¹⁷ kg/year).

J-OFURO2	HOAPS3	OAFflux	ERA40	JRA25	NRA1	NRA2
3.76	3.92	4.45	4.11	6.14	5.38	6.07

Table 3. Global average precipitation (10¹⁷ kg/year).

GPCP2	CMAP	HOAPS3	ERA40	JRA25	NRA1	NRA2
3.23	3.34	3.15	4.21	3.84	3.43	4.05

Table 4. Global budget for freshwater flux (10¹⁶ kg/year).

Evapo.	J-OFURO2	HOAPS3	OAFflux	ERA40	JRA25	NRA1	NRA2
Precipi.							
GPCP2	5.47	7.00	12.31	8.98	29.21	21.66	28.55
CMAP	4.22	5.76	11.06	7.72	27.96	20.40	27.30
HOAPS3	6.23	7.76	13.07	9.73	29.98	22.42	29.30
ERA40	-4.32	-2.77	2.53	-0.82	19.43	1.98	18.77
JRA25	-0.62	0.91	6.22	2.87	23.11	15.55	22.45
NRA1	3.47	5.00	10.31	6.97	27.22	19.66	26.54
NRA2	-2.78	-1.24	4.08	0.73	20.98	13.42	20.32

6. TREND ANALYSIS

Next, we will investigate trend of global budget. Figure 6 shows annual time series of global freshwater flux over the ocean by reference product. We can see increase of freshwater flux from the ocean to the atmosphere. This trend means river discharge and precipitation over the land increases. Figure 7 shows time series of evaporation and precipitation in addition to freshwater flux. Since we can see similar trend only in evaporation shown by blue line, evaporation is crucial to the trend of freshwater flux.



Figure 6. Annual time series of global freshwater flux anomaly over the ocean by reference product.

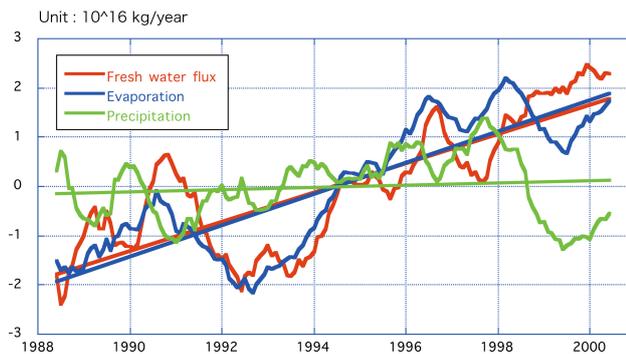


Figure 7. Time series of evaporation and precipitation anomalies in addition to freshwater flux anomaly.

Table 5 shows regression coefficients for evaporation and precipitation. J-OFURO2, HOAPS3, JRA25, and NRA1 give positive significant trend for evaporation. On the other hand, only ERA40 and NRA2 give positive trend for precipitation. In particular the trend by ERA40 seems to be too large.

Table 5. Regression coefficients for (a) evaporation and (b) precipitation

a.

J-OFURO2	HOAPS3	OAFflux	ERA40	JRA25	NRA1	NRA2
0.02	0.03	0.02	0	0	0.02	0.03

b.

GPCP2	CMAF	HOAPS3	ERA40	JRA25	NRA1	NRA2
0	-0.02	-0.01	0.07	0.02	0.02	0.04

Table 6 shows regression coefficients for freshwater flux of each product. Although reanalysis products related to ERA40 and NRA2 show significant negative trend, most products show positive trend. The positive trend suggests increase of precipitation over land and river discharge.

Table 6. Regression coefficients for freshwater flux of each product (unit: 10^{16} kg/month)

Evapo.	J-OFURO2	HOAPS3	OAFflux	ERA40	JRA25	NRA1	NRA2
GPCP2	0.02	0.02	0.02	0	0	0.02	0.02
CMAF	0.03	0.04	0.03	0.01	0.01	0.03	0.04
HOAPS3	0.03	0.04	0.03	0.01	0.01	0.03	0.04
ERA40	-0.03	-0.03	-0.03	-0.05	-0.05	-0.03	-0.03
JRA25	0.01	0.01	0	-0.01	-0.01	0.01	0.02
NRA1	0.01	0.01	0	-0.01	-0.02	0.01	0.01
NRA2	-0.01	-0.01	-0.01	-0.03	-0.03	-0.01	0

Figure 8 is a trend map for the reference product. Evaporation trend is relatively homogeneous and we can see evaporation increases in most regions. On the other hand, we can see large precipitation trends in the tropical regions and the distribution seems to be related to ENSO. As a result, the distribution for freshwater flux shows similar pattern to that of precipitation.

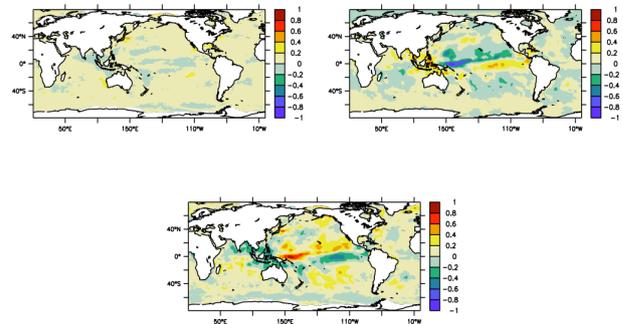


Figure 8. A trend map for the reference product.

7. SUMMARY

We carried out intercomparison of various global freshwater flux products including satellite-products and reanalysis products. In this study we assume GPCP2 precipitation and J-OFURO2 evaporation as reference products. All products can reproduce general common features, for example large freshwater flux from the ocean to the atmosphere can be found in the mid-latitudes so-called ocean desert and that from the atmosphere to the ocean can be found in the tropical regions. However, the freshwater flux values are considerably different depending on each product. Most of products overestimate in the high-latitudes and underestimate in the tropical regions compared with a reference product. We investigate the contribution of each parameter to the deviation between the reference product and other products. For the satellite products the deviation is mostly related to precipitation and air specific humidity. However, for the reanalysis products the deviation is related to all parameters. Wind speed and Q_a contribute to the underestimation and Q_s contributes to the weak overestimation. We also compare meridional profiles. The differences around ITCZ are very large. Also freshwater flux values in the high-latitudes are scattered, including positive and negative values. We investigate global budget of evaporation, precipitation and freshwater flux. J-OFURO2 gives the minimum evaporation and NRA2 gives the maximum value. Also HOAPS3 gives minimum precipitation and ERA40 gives the maximum precipitation. Reanalysis products except ERA40 gives large freshwater fluxes compared with satellite-products because of large evaporation. The reference product gives remarkable positive trend because

evaporation by J-OFURO2 has a positive trend and precipitation by GPCP2 has no trend. Most products show positive trend except products related to ERA40 and NRA2. The positive trend suggests increase of precipitation over land and river discharge. HOAPS3, JRA25, and NRA1 and precipitation by ERA40 and NRA2 show significant positive trends. Both of positive and negative large trends of freshwater flux exist in the tropical regions, similar to precipitation.

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9. ACKNOWLEDGEMENT

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