Estimation of Groundwater Recharge from GRACE Satellite and Land Surface Model

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Abstract*— Due to the dramatic growths of global population and world economy, water use is increasing. Groundwater availability is decreasing in some areas by too much groundwater abstraction. To prevent groundwater depletion, we should develop a tool to evaluate the sustainability of the groundwater use. This study aims to improve a global water cycle model in-land developed by a previous study [1] to simulate groundwater resources storage. To define appropriate amount of groundwater recharge, we compare the seasonal variations of terrestrial water storage (TWS) observed by GRACE satellite. Land surface model SiBUC is used to simulate TWS. There is a strong correlation between time series of simulated and observed TWS in many areas even if we do not include groundwater and river water storage into TWS calculation. The reason why river water storage is not considered is to exclude human activity which strongly affects natural condition. There are no data which indicates how much water is withdrawn from river water, and TWS can change significantly depending on the amount of water withdrawal from river water. By taking groundwater into account, correlation coefficient between the time series of simulated and observed TWS should be improvedif the quality of meteorological forcing data is good enough. Therefore, appropriate groundwater recharge can be determined when correlation coefficient becomes highest value. The amount of groundwater recharge is regarded as the proportion of base flow (q3) simulated by SiBUC, and determining the ratio of groundwater recharge to base flowin the area where ground water withdrawal is negligible is the aim of this research.

***Keywords*—land surface model; terrestrial water storage; GRACE; groundwater recharge**

I. INTRODUCTION

Historically, the amount of global water use have increased twice as fast as population growth [2]. United Nations reported the world population will be 8.6 billion in 2030, and 9.7 billion in 2050 when current population is about 7.3 billion. Such rapid population growth may cause serious water shortage around the world in the future. To prevent such situation, we need to know the accurate amount of water resources in global scaleto maintain sustainable water use. Especially, considering the sustainability of groundwater resources is essential because it is threaten in some areas. Groundwater depletion occurs when the amount of groundwater abstraction excesses groundwater recharge through the year [3].

For this purpose, a lot of global hydrological models were developed, and some models enable to simulate groundwater resources sustainability, for example PCR-GLOBWB [4], WaterGAP [5], HiGW-MAT [6] or H08 [7]. Shiojiri et al. [8] also simulated global water cycle in-land. In this research, the model developed by Kotsuki et al. [1] is improved to simulate groundwater resources storage. The characteristic of the model is physical representation of the irrigation water requirement in the water balance calculation. Furthermore, normalized difference vegetation index (NDVI) derived from satellite observation is used to determine the crop calendar. By using satellite data, sowing date can be identified more accurately with higher resolution compared to agricultural statistics based data Shiojiri et al. [8] visualized the non-sustainable groundwater use areas using this model. However, the result is not verified, and groundwater recharge is assumed to be 20 % of base flow. This assumption is insufficient to achieve accurate evaluation. Therefore, this research aims to simulate more accurate groundwater recharge.

To obtain better groundwater recharge, simulated terrestrial water storage (TWS) is compared with GRACE (Gravity Recovery and Climate Experiment) satellite data. Terrestrial water storage is the total amount of water in and on the ground. GRACE does not observe groundwater directly, but it is an only satellite which can observe the mass change of groundwater resources. Other models which can simulate the volume of groundwater resources (WaterGAP ,HiGW-MAT and H08) do not use satellite data to simulate groundwater recharge, but use the method originally derived from field observation in most of cases. It will be difficult to acquire accurate evaluation of groundwater resources sustainability by applying the method developed in local scale to the simulation in global scale. PCR-GLOBWB3) calculates groundwater recharge using only global elevation dataset, and this may be too simple to simulate groundwater recharge precisely. On the other hand, by analyzing the result of spatial pattern given from satellite, the groundwater recharge rate can be parameterized reflecting the diverse characteristics of each grid cell.

II. METHODS

A. Model

Our model developed by Kotsuki et al. [1] is a distributed model consisting of land surface model SiBUC (Simple Biosphere Model including Urban Canopy) [9] and river routing model (kinematic-wave theory), but we improve only land surface model SiBUC in this research. Fig. 1 shows a schematic diagram of SiBUC. This model simulates water balance in a vertical direction by giving meteorological forcing data and land surface parameters as input data. Not only water balance but also heat and radiation balance are solved, and it makes the water balance simulation highly accurate

In SiBUC, soil layer consists of three layers and waterbalance is calculated between those layers. The equations indicating water exchange between those layers are derived from Darcy's low. First soil layer is surface layer and evaporation occurs from this layer. Second soil layer is root zone where transpiration occurs. Third soil layer is recharge zone, and base flow (q3) is obtained as drainage water from this layer. The volume of base flow is determined based on the sine component of mean topographic slope.

$$q_3 = k_s W_3^{2B+3} \sin\theta \qquad (1)$$

Where k_s is saturated hydraulic conductivity, W_3 is soil wetness in third soil layer, B is a parameter depending on soil type, and θ is mean topographic slope. In this equation, the excess water in the third soil layer is drained along the slope. However, a proportion of drainage water from recharge zone should infiltrate to the deep groundwater layer. Therefore, we assume groundwater recharge to be some proportion of base flow

$$rech = \alpha(q_3 - \overline{q_3}) \qquad (2)$$

Where $\overline{q_3}$is annual mean base flow, and α is an undetermined coefficient. To reflect seasonal variation of groundwater resources storage, we estimate groundwater recharge by this equation. Identifying α appears in this equation is the objective of this research.

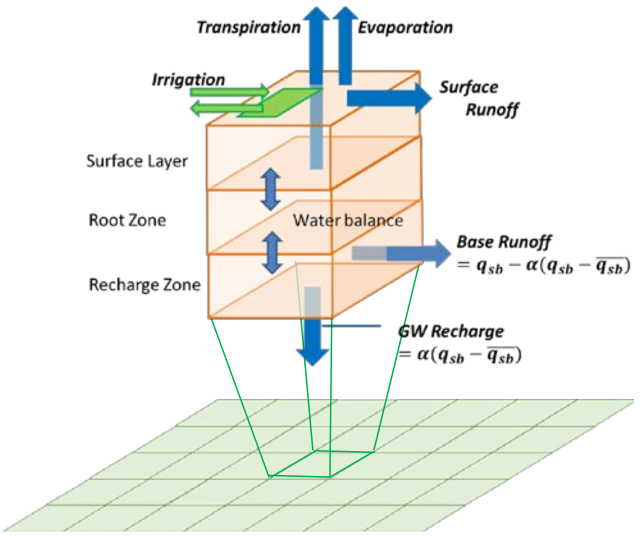

Fig. 1 Schematic diagram of SiBUC

B. Land surface and vegitation parameters

As soil and vegetation input, Ecoclimap offered by METEO France. For 1km elevation and land use, GTOPO30 and GLCC v2.0 offered by USGS (U.S. Geological Survey) are used. At the same time, MIRCA2000 [10] is used for the distribution of irrigated crop area, global rain-fed agricultural area, and crop type data. After making land cover ratio of irrigated and non-irrigated crop land using GLCC v2, it is modified to be same as MIRCA2000.

C. Meteorological forcing data

In this research, we conduct the simulation at the period of 2002 to 2017. Meteorological forcing data is required to run the model. We used Japanese 55-years reanalysis (JRA55) in this research. However, global total of yearly precipitation is much larger than other product or the datasets used other researches shown in TABLE 1. Therefore, we corrected precipitation using GPCC v6 and APHRODITE v1101. Both products are made based on field observation data. GPCC covers all over the world and APHROSITE covers Eurasian continent but mainly Asia. More observation data is used to make APHRODITE than GPCC. Thus, we used APHRODITE if there is data, or we used GPCC. However, these datasets are available only until 2006. We calculated whole period average of monthly precipitation from 2002 to 2006 and corrected JRA55 precipitation by following equation.

TABLE 1 Global total of yearly precipitation in-land [Gt/yr]

JRA55	144,840
GPCC_v6 and APHRODITE v1101	110,518
Kotsuki et al. (2012)8)	99,863
Baumgartner and Reichel (1975)11)	111,000
Hanasaki et al. (2007)12)	108,000

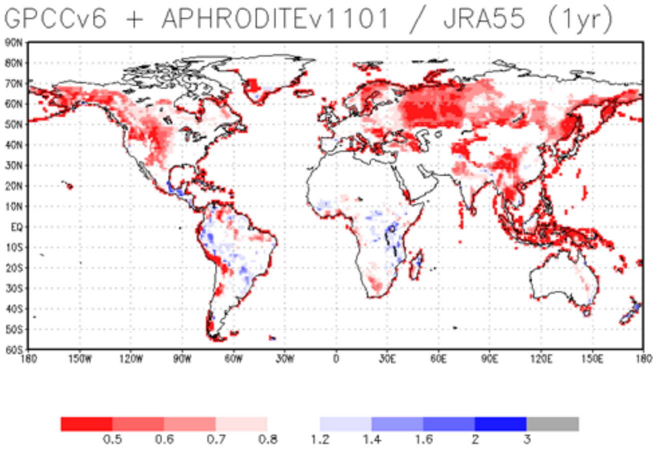

Fig. 2 Yearly average of multiplied ratio used for precipitation correction

$$P^{JRA}_{corrected} = P^{JRA}_{raw} \times \frac{P^{GPCC+APHRO}_{mon,ave}}{P^{JRA}_{mon,ave}} \qquad (3)$$

This correction is applied only when monthly precipitation exceeds 10mm. In *Fig. 2*, yearly average of multiplied ratio is shown, but the grids whose monthly precipitation is less than 500mm are not displayed. In this figure, large difference is contained between these products. Overestimation is seen especially in Southeast Asia, and there are a lot of grids whose precipitation is 1000mm ~ 2000mm in APHRODITE but more than 3000mm in JRA55.

III. RESULTS

A. *Method of TWS simulation*

We simulate TWS using SiBUC with following equation.

$$TWS = SM + SWE \qquad (4)$$

Where SM is soil moisture and SWE is snow water equivalent. On the other hand, GRACE measures the change of total volume of water on and in the ground, and groundwater storage, river water storage and reservoir water storage are also included. However, they are not considered in our simulation. The reason why groundwater storage is not considered is that it is not modeled yet and modeling of this part from the comparison of TWS is the goal of this research. Regarding river and reservoir water storage, we exclude them to eliminate the impact of human activities. There are no data which indicates how much water is withdrawn from river water, and it depends on how water withdrawal is expressed in the model. Therefore, the distribution of the amount of river water withdrawal varies from model to model. If river and reservoir water storage are considered for TWS simulation, groundwater recharge derived from TWS comparison will differ from actual one. Thus, we consider only variables outputted by SiBUC and reproduce groundwater rechargein the area where groundwater withdrawal is negligible.By finding out the relationship between the ratio and the characteristic of the grid, we will be able to parameterize the ratio in the area human activities affect TWS variation.

This simulation is conducted from 2002 to 2017 at 1degree spatial resolution. GRACE data is offered monthly from April 2002 to January 2017 at 1 degree after smoothed when original resolution is 300km. We selected the same resolution as offered GRACE data for this simulation. When we compare simulated TWS with measured one, we use average of three solutions (CSR, GFZ and JPL) as observed TWS to reduce the noise [13].

B. *Comparison of time series of TWS*

We compared the time series of observed and simulated TWS. Here, we introduce the results of some peculiar grids. Simulated TWS shown in the graphs is adjusted for the average of whole period to be the same as the one of GRACE. This is because measured TWS is not the absolute quantity but the variation.

Fig. 3 shows the time series of TWS in the center of Brasil. In this figure, both TWS time series overlap clearly and our simulation reproduces TWS in this region very well. This is because there is much precipitation in this area and main factor of TWS change is soil water. The impact of soil water against TWS variation is too large for groundwater or other factors to affect.

Fig. 4 shows the result at a grid in Thailand. These two lines fit well. *Fig. 5* shows the result without correcting precipitation at the same grid as *Fig. 4*. Simulated TWS changed significantly, and correlation coefficient decreased. Therefore, we could confirm precipitation correction is necessary.

Fig. 6 shows the result at the center of Greenland. In the GRACE variation, decreasing trend is seen. This is caused by glacier melting. [14] However, our simulation cannot reflect the effect. We have to improve our model to simulate glacier melting. When the decreasing trend seen in GRACE is removed, the influence of glacier melting should be smaller, and the time series changed to *Fig.7*. By removing trend, correlation coefficient increased a little and RMSE decreased. This means our model could simulate TWS without glacier well.

In *Fig. 8*, the result at a grid including New Delhi is shown. Groundwater depletion occurs in New Delhi [15], and we can see the decreasing trend caused by it in GRACE time series. We do not consider groundwater for TWS calculation, this decreasing trend is not seen in simulated TWS. However, when the decreasing trend is removed, correlation coefficient increased and RMSE decreased (*Fig. 8*). Therefore, we can confirm that our simulation can reproduce TWS without human

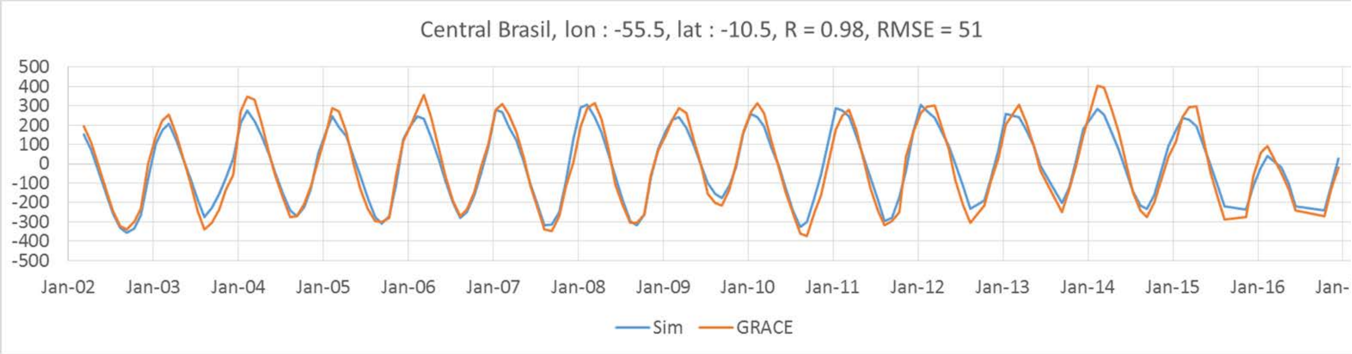

Fig. 3 Time series of TWS in the center of Brasil

activities well.

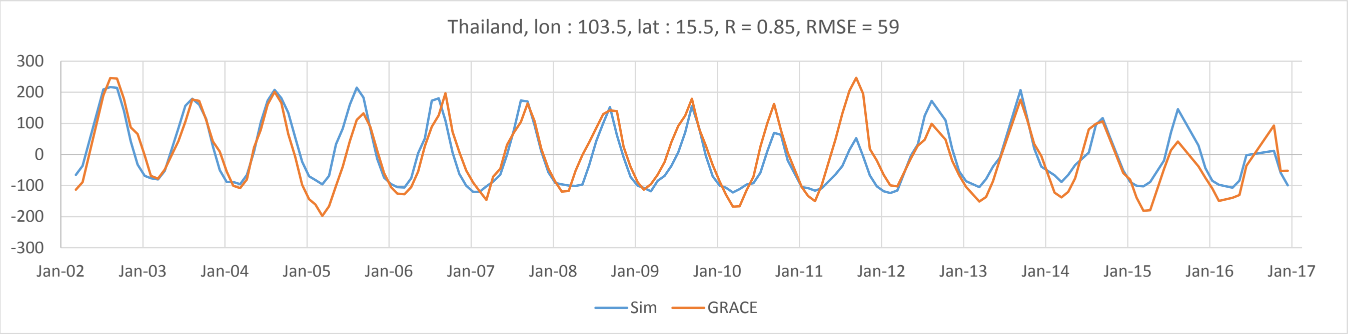

Fig. 4 Time series of TWS at northeast part of Thailand

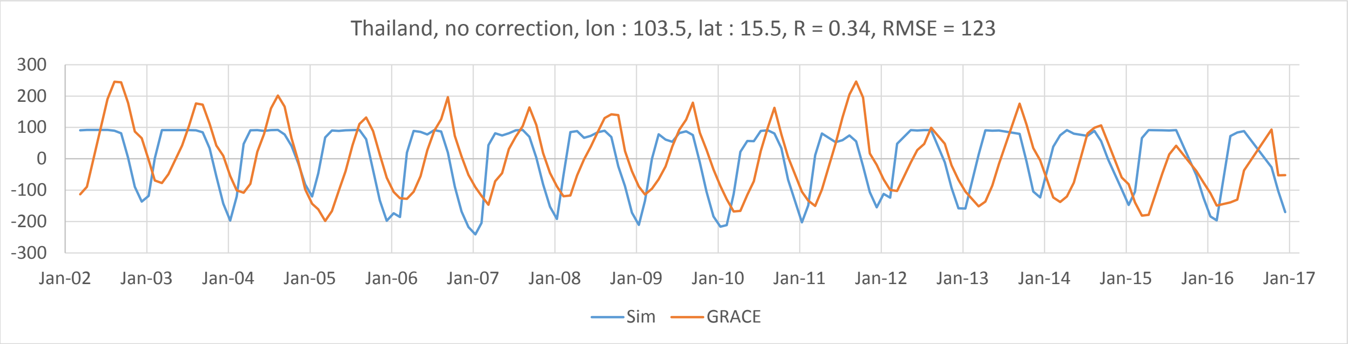

Fig. 5 Time series of TWS without precipitation correction at the same grid as Fig. 4

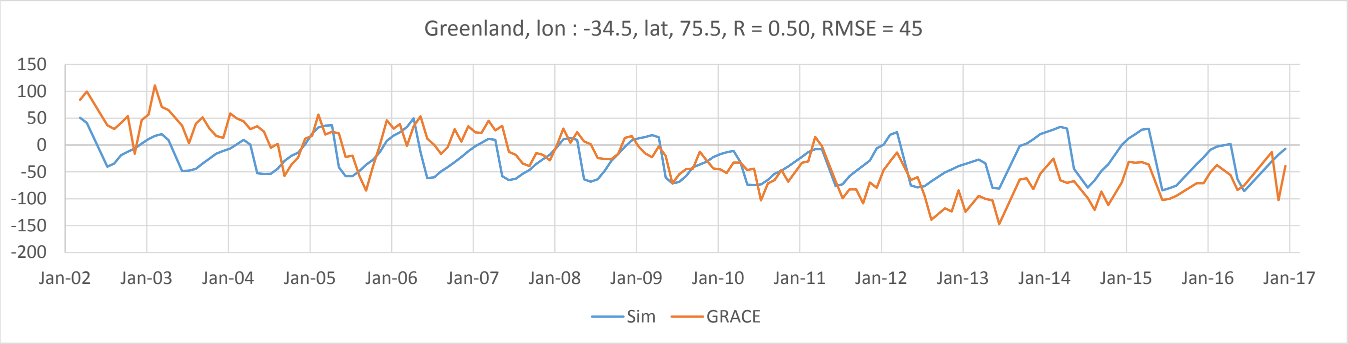

Fig. 6 Time series of TWS at the center of Greenland

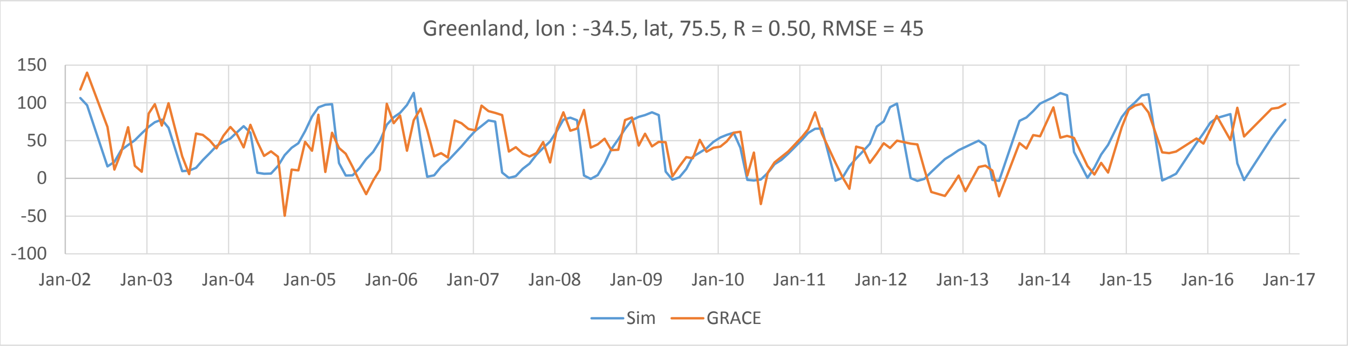

Fig. 7 Time series of TWS removed trend from GRACE at the same grid as Fig.6

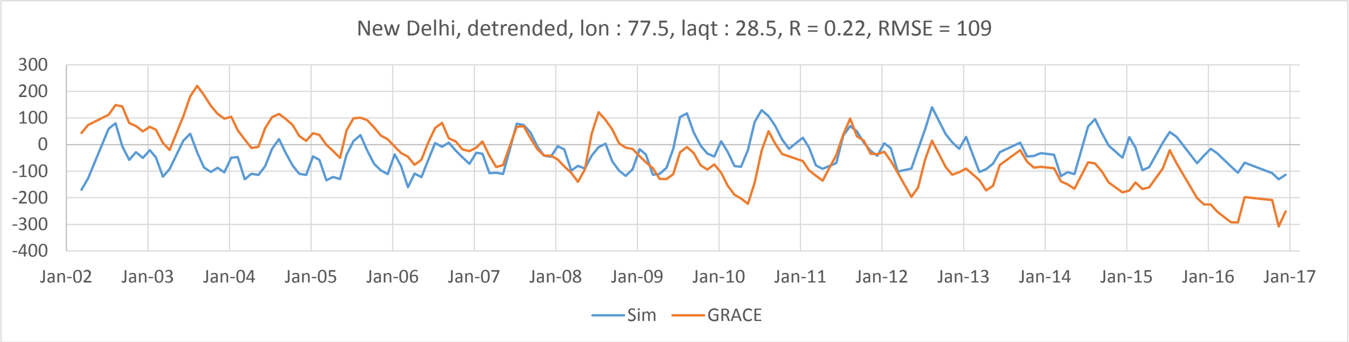

Fig. 8 Time series of TWS at a grid including New Delhi, India

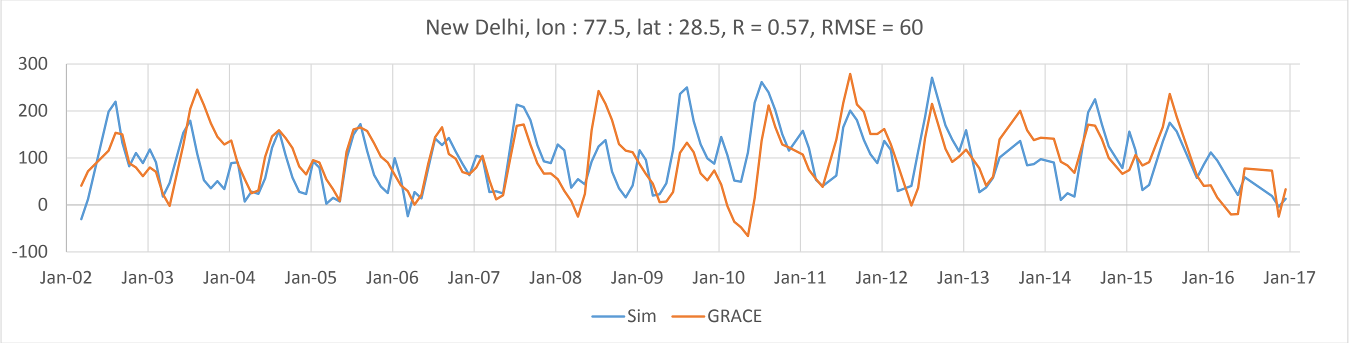

Fig. 9 Time series of TWS removed trend from GRACE at the same grid as Fig. 8

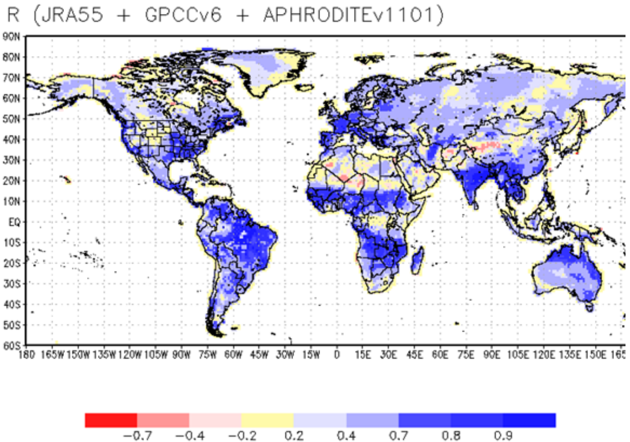

Fig. 10 Correlation coefficient of time series of simulated and observed TWS

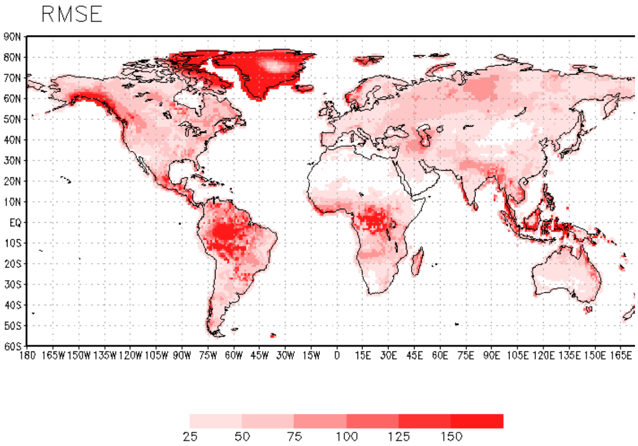

Fig. 11 RMSE between simulation and observation

C. *Evaluation of simulation accuracy*

We compared the time series of simulated and observed TWS representatively shown in *Fig. 3~9* at all grids. To evaluate the simulation accuracy, we calculate correlation coefficient and root mean square error (RMSE). *Fig.10* shows correlation coefficient and *Fig. 11* shows RMSE. In *Fig. 10*, strong correlation is seen at a lot of grids. However, correlation coefficient becomes low in some areas, for example north of Africa. This is because variation range of TWS is too small. In *Fig. 11*, RMSE is small in north of Africa or other grids where correlation coefficient is low, and this means the average of the difference between simulated and observed value is small. Although seasonal variation seen in measured TWS is not reproduced, the absolute quantity is reproduced well. Therefore, the accuracy of the simulation is confirmed at almost all grids.

D. *Estimation of groundwater recharge*

It is confirmed that TWS simulation is accurate enough without considering groundwater, river water storage or reservoir water storage. When accurate groundwater is added to TWS, correlation coefficient should be improved. We try to estimate groundwater recharge by this comparison of correlation coefficient.

Groundwater recharge is assumed to be the proportion of base flow. We estimated αappears in (2) which is necessary to calculate groundwater recharge from the comparison. At first, we added groundwater to TWS with various αvalue. Next, we calculate the correlation coefficient between GRACE data and the TWS including groundwater. When the correlation coefficient became maximum, we assumed the ratio as appropriate value. Estimated α is shown in *Fig. 12*. In this figure, there are many grids whose value is 0 or 1. When $\alpha$is 0, it means the variation of simulated SM and SWE is too large. On the contrary, when the ratio is 1, simulated SM and SWE are small or the influence of river water storage or human activity is large. However, we do not validate the accuracy of α. To confirm the accuracy, we have to examine whether there are the relationships between the ratio and the characteristic of the grid, for example slope, soil type, elevation, and so on. If we can find out the relationship, parameterization of αin global scale becomes possible, and we can evaluate the influence of human activities by comparing GRACE data and simulated TWS including groundwater and human activities.

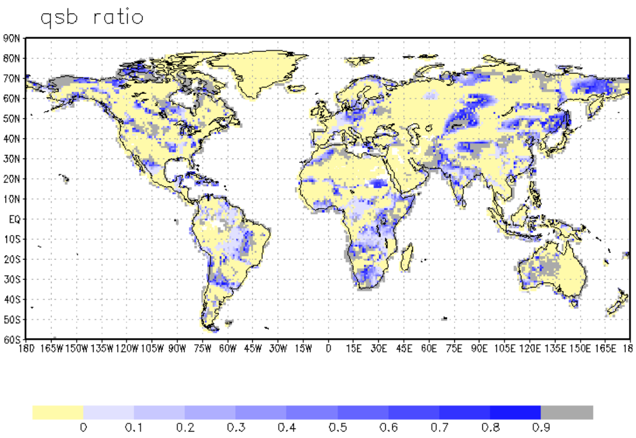

Fig. 12 Estimated α in (2)

IV. CONCLUSION

We simulated TWS as sum of SM (soil moisture) and SWE (snow water equivalent) to estimategroundwater recharge fromthe comparison with GRACE satellite data. At that time, we did not consider groundwater, river water storage and reservoir water storage in order to eliminate the influence of human activities. Therefore, we could not reproduce the decreasing trend measured by GRACE whose cause is too much extraction of groundwater. This will be reproduced after we can estimategroundwater recharge appropriately. Long term decreasing trend caused by glacier melting was not reproduced either because we did not incorporate that module. Evaluation of glacier melting will be possible by putting a lot of snow as initial condition on the ground in a land surface model.

By comparison with GRACE satellite data, we could confirm our simulation reproduced TWS well. If groundwater is included into TWS calculation, correlation coefficient should be higher. Therefore, we added groundwater to TWS with various αwhich appears in (2), and we assumed α to be the appropriate value when correlation coefficient becomes maximum. By this method, we could estimate α and groundwater recharge. To find out the relationship between the ratio and the characteristics of the land is a future work. Using other satellite datasets is also a future work in order to separate each component of TWS. For example, we can separate soil moisture by using SMAP, or SMMR enables to separate SWE. More accurate groundwater recharge will be obtained by these satellite datasets.

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