Validation of JRA-JCDAS LDA and GRiveT Terrestrial Water Storage Model Using GRACE Satellite Gravity Data

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INTRODUCTION

Since the successful launch in 2002, dedicated satellite gravity mission GRACE (Gravity recovery and Climate Experiment, Tapley et al., 2004) has provided monthly gravity field solutions as spherical harmonic coefficients with unprecedented accuracy. The mass variations derived from the gravity field solutions can be interpreted geophysical signals accompanying mass movements, e.g. landwater movements, ocean circulation, ice sheet mass changes, post glacial rebound, mass changes associated with earthquakes, and so on. Among them, one of the most promising is the monitoring of landwater movements. Since the initial stage of the mission, it has been confirmed that the seasonal mass variations obtained from GRACE data correlate well with global terrestrial water storage model GLDAS (Global Land Data Assimilation Systems, Rodell et al., 2004), especially in large scale and so as other global landwater models, e.g. LaD (The Land Dynamics Model, Milly and Shmakin, 2002) or WGHM (WaterGAP Global Hydrology Model, Guntner et al, 2007), and so on.

Because GRACE satellite observes vertical integration of mass variation of the Earth, it can detect total landwater variation including groundwater. This is one of the advantages to use GRACE data for the study of landwater movements and is useful to improve landwater models. In regional scale, some differences are shown between GRACE seasonal signal and models' ones both in amplitude and phase. One of the considered reasons is that most of global landwater models do not considered groundwater components sufficiently because of the difficulty of the observation.

In Japan, JRA-JCDAS LDA and GRiveT Terrestrial Water Storage Model (JLG) has developed by Nakaegawa et al (2007). Yamamoto et al. (2007) compared GRACE mass variation with the previous version of JLG model in four major river basins of the Indochina Peninsula. The result shows that the annual phase of the model are gained about 1 month compared to the GRACE mass variations model's one. The phase discrepancy in the Indochina Peninsula was improved in the new version of JLG model by considering groundwater component explicitly with current speed tuning for each river basins (Fukuda et al., 2008). Thus, at least, in the Indochina Peninsula, it is confirmed that GRACE data is useful to improve JLG model. However, in other river basins, the comparison between the two data sets has not been performed yet. Thus, in this study, we compared annual components of the terrestrial water storages obtained JLG model with the ones of GRACE mass variations for major river basins in the world. However, the result shows that at least in this stage, we could not obtain sufficient result especially in amplitude. This problem mainly comes from the difficulty of determination of scaling factor of the filtering function. We also review and discuss problems of filtering methods and the scaling methods.

TEST AREAS

We selected 70 major river basins defined in JLG model as test areas for the estimation in this study. The geographical distribution of the basins is depicted in Figure 1. The maximum river basin is Amazon (basin no. 1

in Figure 1). The area is 6.2 x 10^6 km^2 and corresponds to spatial scale of about 800 km. The area of minimum basin (no. 68, Odra) is 1.1 x 10^5 km^2, about 350 km spatial scale. Although in practice, it is probably difficult to recover the landwater signal in such small area because of the increase of satellite measurement error in short wavelength, we also attempted to recover the mass variation under considering the GRACE data used in this study is up to degree/order 60, which corresponds to about 330 km in spatial scale.

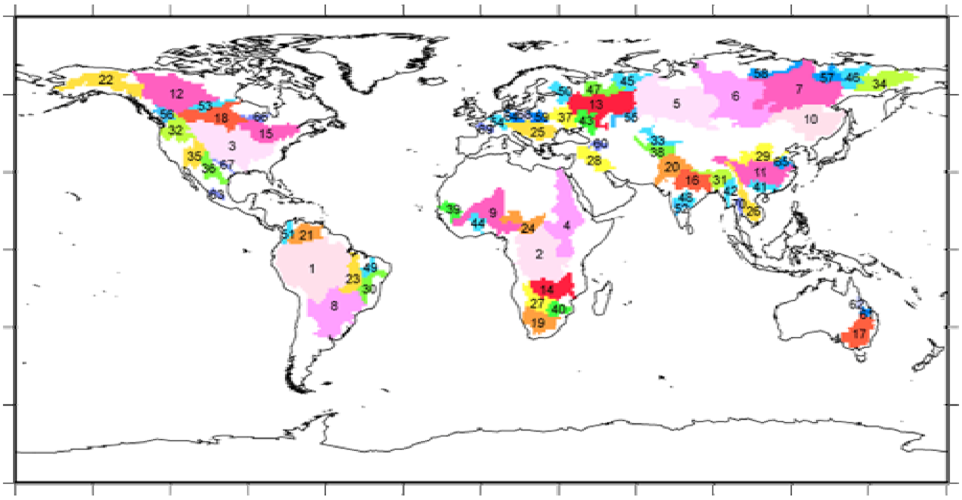

Figure 1. Geographical distribution of the 70 river basins estimated and validated the mass variations in this study.

GRACE DATA AND PROCESSING

UTCSR RL04 version of GRACE Level 2 monthly gravity field solutions were used in this study. The solution is provided as spherical harmonic coefficients up to degree/order 60, which corresponds to 3^o of spatial resolution. We used 59 monthly solutions from April 2002 to May 2007. Because the large error is reported, C_{20} values were replaced to the SLR solutions (Cheng and Ries, 2007). To obtain the variable components, the average of the 59 data sets were subtracted from each solution. Mass variations of 70 river basins were estimated by regional filtering method (Swenson et al, 2003). That is, optimized filter was designed for each river basin so that the sum of signal leakage error and satellite measurement error become minimize by least squares method. The leakage effect was estimated by Yamamoto et al. (2007). The signal degradation by the filtering was corrected by multiplying the scaling factor to the filter function. In this study, the scaling factor was determined as follows although there are some problems as stated in the discussion chapter. That is, we compared degree amplitudes of the model and the filtered GRACE data inside the test area, and determined the constant scaling factor so that the scaled GRACE degree amplitude fit well as possible with the model's degree amplitude.

JLG TERRESTRIAL WATER STORAGE MODEL

JLG is one of the global terrestrial water storage models developed by Nakaegawa et al (2007). The total terrestrial storage obtained from JLG consists of soil moisture, snow water equivalent, river water storage and groundwater storage. Soil moisture and snow water equivalent are obtained from JMA-Simple Biosphere model (JMA-SiB). These two components are the same ones of JRA-25 reanalysis and JCDAS objective analysis. River water storage and groundwater storage are obtained from offline simulation performed with MRI Global River Model for TRIP (GRiveT). The temporal and spatial resolutions are 6 hour and 1^o, respectively. More detail schemes of the computation of this model are stated in Fukuda et al. (2008).

Although we mainly discuss landwater mass variation, the combined model of landwater and ocean were made and used in this study for the purpose of comparison with GRACE and the model power in spectral domain. Estimating the Circulation and Climate of the Ocean (ECCO) model (Kalman filter run, version kf066b) is used as

the ocean area model. However, in practice, the power of ocean signal is small, which is about order of one smaller than that of landwater. We omitted and set to 0 of the Antarctica and Greenland data, because of the extremely unnatural variations, although it may cause some underestimation of total power of the model.
For the correspondence with GRACE data, the averages of the combined model data corresponding to the time period of GRACE monthly solution and the variable components were obtaining by subtracting the monthly data average of the whole time span. Considering global mass conservation, degree 0 terms of variable components were set to zero at each time by distributing residual mass to the ocean area uniformly. Degree 1 terms were omitted in the calculation and regional average of each major basin was computed by using only up to degree/order 60 in spherical harmonics.

COMPARISON OF ANNUAL PHASE

For the 70 major river basins shown in Figure 1, the annual phases and amplitudes of the model and the GRACE mass variations were compared with each other. Figure 2 shows the difference of the annual phases (JLG minus GRACE) of each river basin. In several basins, the differences are relatively large. For the basins with the phase difference above 2 month, annual mass variation is investigated more detail. Most of these differences (of the basin no. 6, 28, 43, 52, 54, 67 and 70) come from the error of GRACE signal. Because of the large errors at some data points, annual fitting of GRACE mass variation become inaccurate and as a result, it causes the phase difference. If such bad data point is removed for the estimation of annual signal, the phase correlation of these river basins is expected to be improved. In the basins of no. 62 and 64, JLG data shows annual mass variation, while GRACE data does not. Most possible reason of the discrepancy is that GRACE could not recover reliable mass variations in these areas because of the small spatial scales. In the basins of no. 10, 17, 36, 46, annual components is not prominent in addition to the low correlation of total signals. As a result, in these basins, the phase difference looks large. In other river basins, the phases of the GRACE and JLG data sets show relatively good correspondence. Thus, although it means that the current version of the JLG model relatively well represents the annual terrestrial water storage including groundwater, the phase differences are not completely zero in most of these river basins. Thus in most basins, GRACE data will give a constraint to the annual phase for the tuning of the model and it is expected to be useful for further improvement of JLG model.

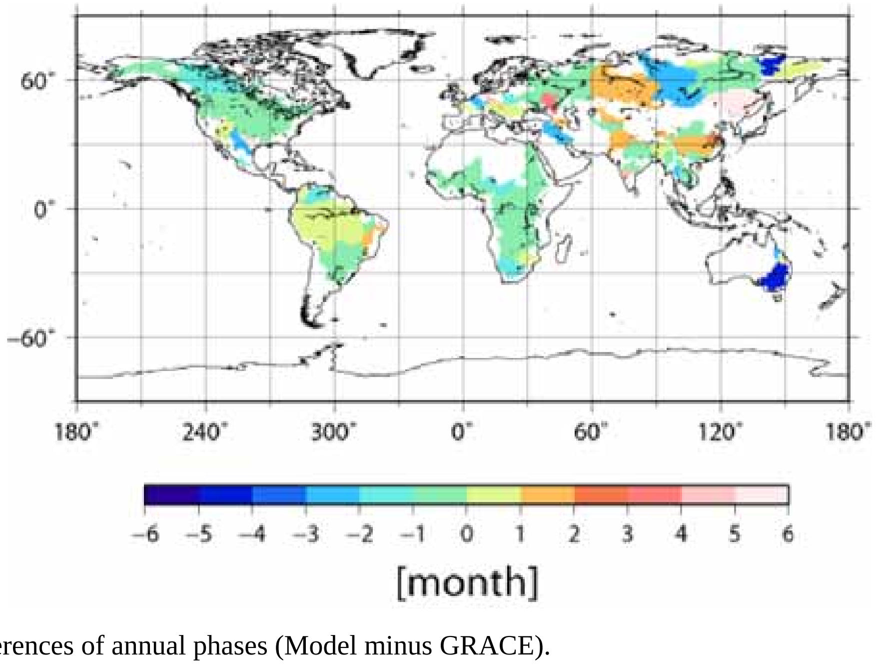

Figure 2 The differences of annual phases (Model minus GRACE).

CURRENT PROBLEMS OF ESTIMATION OF ANNUAL AMPLITUDE

For the recovery of mass variations from GRACE Level 2 solutions, filtering processes are generally used to reduce large errors especially in short wavelength and several filters have been developed for the purpose, e.g. Wahr et al.(1998), Swenson et al. (2003), Han et al. (2005), Seo and Wilson (2005), and so on. These filters have different characteristics, and contain different parameters to determine intensities of the filters. The problem is that the intensities of the filter are relatively sensitive to the value of parameter in most of these filters and the optical values of these parameters are generally unknown. Werth et al. (2007) investigated the characteristics of several filters and the sensitivity for parameters. They concluded that optimal filtering method and its optimal parameter differ by each basin depending on the shape, size, location, signal properties, and leakage error properties. In case of the regional filter of Swenson et al. (2003) used in this study, two parameter is required; i.e. a correlation length of the filter and error variance. The optimum values of these parameters are unknown and even in exponential base function, which has relatively small sensitivity to correlation length compared with Gaussian base function, the sensitivity is relatively large and cannot be ignored.

For the comparison with the model with the filtered GRACE data, one of the approaches is to apply the same filter to the model value. This method is useful to know how the spatial pattern is degrading by applying the filter. However, the magnitude of the obtained model signal cannot compare with the GRACE value directly because of the GRACE error is not contained in the model.

Another approach is to estimate signal degradation of the filter and correct the degraded value by multiplying the scaling factor. For example, for the estimation of Greenland ice sheet mass change, Velicogna and Wahr (2005) assumed an uniform mass change over Greenland, and determined scaling factor so that the filtered average Greenland value become the same value before the filtering. However, this method does not work well with low latitude landwater estimation, and one of the considered reasons is the difference of signal property of the test region.

In this study, we also estimated the true signal amplitude by multiplying scaleing factor. As snown in GRACE data processing chapter, we determined the scaling factor of the filter by assuming that the spectral behaviors of the GRACE and model data become same in the regional area. Because we used the model's spherical harmonics as the predicted 'true' signal spectrum to determine the scaling factor, we could not discuss by comparing the amplitude of the GRACE and the model signal because the filtered GRACE amplitude essentially become similar value by the scaling with the model. Figure 3 shows the ratios of the amplitudes (JLG value with respect to the estimated GRACE signal) in each region. In several basins, the ratios show extremely large values. Most of these basins correspond to the areas stated in the phase discussion and the same reason can be applicable for the amplitude estimation. That is, 1) the areas with the small S/N ratios because of the small signal or small spatial scale, 2) the areas which the annual components cannot be estimated with reliable precision because of errors at some data points, or 3) the areas with non significant annual components. In other basin, the estimated amplitude of most of river basins shows good correspondence with the model's amplitudes except some very large basin. It shows that the spectral behaviors between the filtered regional GRACE signal and the model's regional signal are similar with each other in these basins.

On the other hand, in some large basins like Amazon (no.1), Misissipi (no. 3), or Congo (no. 2), the estimated GRACE annual amplitudes are about 3 to 6 times larger than the model's ones. It is because, in spectral domain, the degree valiances of the regional filtered GRACE signal and the regional model signal of these areas show relatively large difference especially in long wavelength. One of the considered regions of such discrepancy of the long wavelength spectrum is that the underestimation of the model's long wavelength power. In this study, the model's signals over Antarctica and Greenland were omitted in our estimation for the extremely large errors and the omission is probably gives some errors in long wavelength spherical harmonics. Another possibility is the underestimation of GRACE error especially in long wavelength. In the filtering method of Swenson and Wahr, the error spectrum is important parameter for the design of the regional filter and we used calibrated standard deviations released by GRACE data center as the GRACE's error level. If the error estimation is inaccurate, the spectral behaviors of the filter functions also become inaccurate. Thus it is important to investigate the behavior of signal and error in long wavelength near future.

Ideally, for the validation of the model signal, it is of course best to use the spectral behavior of the 'true' signal should be determined by GRACE signal for the determination of scaling factor. However, as shown in Figure 4, in spectral domain, degree variance of the variable components of GRACE data is apparently large compared with the one of the sum of the model's signal and the released calibrated standard deviation of GRACE data. It means that the power of the GRACE error or/and the model's signal is underestimated. Therefore, in this study, although we used the model's spherical harmonics as the predicted 'true' signal spectrum, it is very important for the validation of future model's amplitude to asses the spectral property of GRACE error, which has not been sufficiently investigated at this stage.

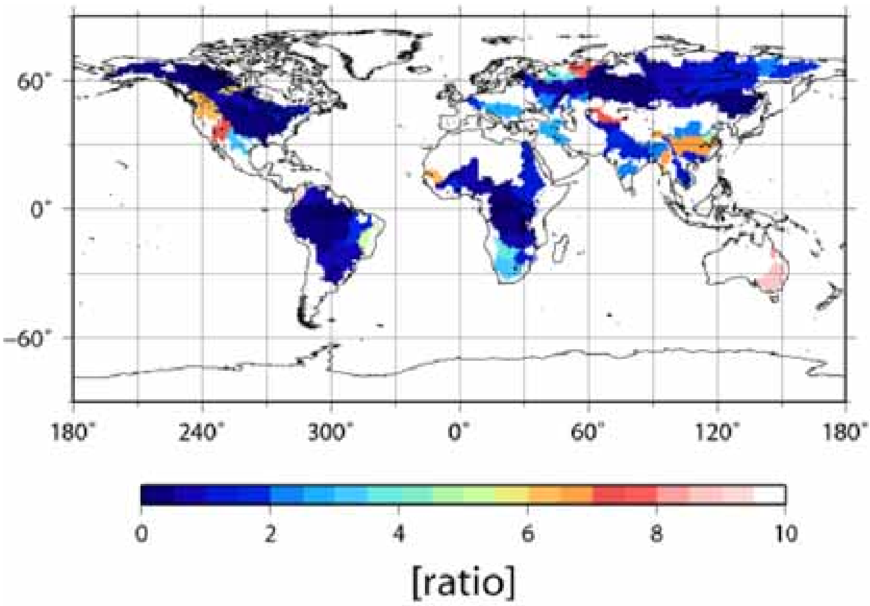

Figure 3. The ratios of estimated annual amplitudes (Model/GRACE).

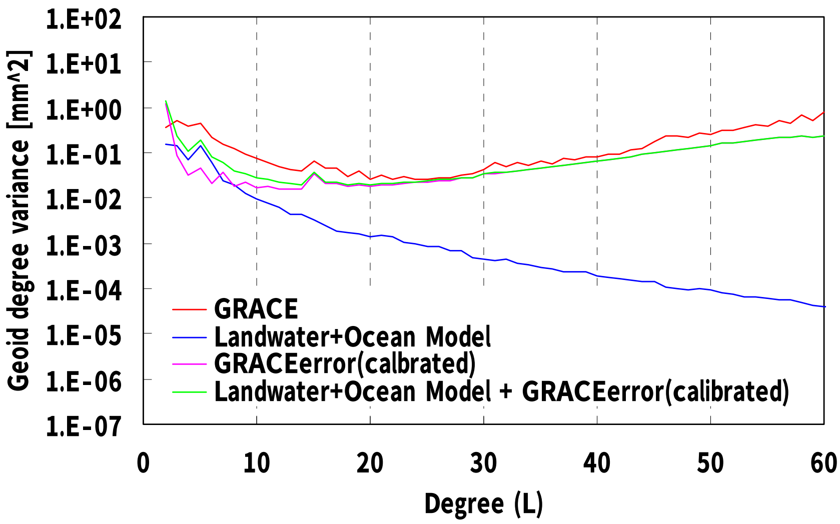

Figure 4 Degree variance of the variable components of GRACE, Landwater and Ocean combined model, GRACE calibrated standard deviation, and model plus the calibrated standard deviation.

CONCLUSION

At this stage, in our method, it is difficult to validate model's amplitude using GRACE accurately as discussed above. However, one of the large merits to use GRACE data is to assess and improve the landwater variation with considering global water balance. For such purpose, it is very important to investigate error level of GRACE signal, not only short wavelength but long wavelength and this is future work. Although the determination of the scaling factor of the filter has large problems at this stage, the phase information is not probably largely changed by the change of the factor. Thus, the result in this study is at least useful to constrain annual phase for the tuning.

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