Validation of the land water storage simulated by Organising Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) with Gravity Recovery and Climate Experiment (GRACE) data

T. Ngo-Duc,[1,2] K. Laval,[2] G. Ramillien,[3] J. Polcher,[2] and A. Cazenave[3]

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[1] The Gravity Recovery and Climate Experiment (GRACE) mission provides measurements of spatiotemporal change in land water storage that may improve simulation results of land surface models (LSMs). We show that a transfer scheme recently developed within the Organising Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) LSM significantly improves the simulated land water storage. Over large tropical rivers basins, model results without the transfer scheme provide significantly smaller amplitudes of water storage than observed by GRACE. Including the transfer scheme that accounts for water stored in the river systems and aquifers during its transfer to the oceans leads to predicted land water storage that are comparable to GRACE observations. Water stored in aquifers contributes about half the seasonal variation of water storage over large basins such as the Amazon, Congo, Yangtze, Ganges, Brahmaputra, and Mekong.

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1. Introduction

[2] Water and energy exchanges at the soil-vegetation-atmosphere interface play a major role in the Earth's climate. This connection has motivated the climate modeling community to develop more realistic land surface models (LSMs). A LSM forced by meteorological data and specific surface characteristics (vegetation types, soil information) simulates processes at the surface-atmosphere interface, such as vegetation and soil water dynamics, and water, energy and carbon exchanges. However validating model results is not always feasible because in situ observations are lacking at global scale.

[3] Since mid-2002, the space gravimetry mission GRACE, developed by the National Aeronautics and Space Administration in the United States and the Deutsches Zentrum für Luft und Raumfahrt in Germany, provides time-variable gravity field solutions with unprecedented precision and resolution [*Tapley et al.*, 2004a]. These monthly gravity field solutions can be expressed in terms of vertically integrated terrestrial water storage over continental areas with a resolution of $\sim$500 km, and a precision of a few cm in equivalent water thickness [e.g., *Swenson et al.*, 2003; *Tapley et al.*, 2004b; *Wahr et al.*, 2004; *Rodell et al.*, 2004; *Ramillien et al.*, 2005; *Schmidt et al.*, 2006]. The main goal of these studies was to validate the GRACE data by comparing GRACE-based land water storage with LSM output. They showed that GRACE-based water mass changes over the continents agree reasonably well with LSM predictions. However there are some discrepancies among model predictions because of different modeling approaches and forcing observations. *Swenson and Milly* [2006] compared water storage from GRACE with outputs from five climate models and found systematic model biases at low latitudes. Seasonal extrema of low-latitude hemispheric storage generally occur too early in the models, and model-specific errors in amplitude of the low-latitude annual variations are substantial.

[4] In the present study, we compare the land water storage simulated by ORCHIDEE LSM developed at the Institute Pierre Simon Laplace, France with GRACE-based land water solutions computed by *Ramillien et al.* [2005]. We focus on large tropical river basins where land water storage predicted by other models is not coherent with observed values [e.g., *Swenson and Milly*, 2006]. We show that a transfer scheme which takes into account the storage of drained water flowing toward oceans, leads to better agreement between water storage variation estimates from ORCHIDEE and GRACE.

2. Data and Numerical Experiments

2.1. GRACE Data

[5] Global GRACE-based gravity fields solutions since April 2002 are available. Each solution consists of a set of spherical harmonic coefficients, C_{nm} and S_{nm}, of the geoid (equipotential surface of the gravity field), complete to degree and order $\leq$120. Subscript n and m are degree and order of the spherical harmonic expansion.

[1]Institute of Industrial Science, University of Tokyo, Tokyo, Japan.
[2]Laboratoire de Météorologie Dynamique, CNRS, Université Pierre et Marie Curie, Paris, France.
[3]Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, CNES, Toulouse, France.

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[6] The gravity variations that GRACE is able to detect include vertically integrated changes in different reservoirs: changes as a result of surface and deep currents in oceans; changes in distribution of water and snow stored on land; mass changes of the ice sheets and glaciers; air and water vapor mass change within the atmosphere; and variations of mass inside the solid Earth. During the GRACE data processing, atmospheric and ocean mass change are taken into account using atmospheric mass and barotropic ocean circulation models. The remaining GRACE gravity solutions mostly reflect land water and ice mass change. In this study we use the GRACE land water solutions computed by *Ramillien et al.* [2005] using the first released GFZ (GeoForschungsZentrum Potsdam) geoids. The land water solutions from *Ramillien et al.* [2005] are based on a generalized least squares inversion of the GRACE geoids. To constrain the inversion, independent information derived from outputs of the global atmospheric, hydrological and oceanic models are included. A detailed description of this inversion method is given by *Ramillien et al.* [2004, 2005]. Depending on choice of the inversion algorithm, retrieval of land water storage phase and amplitude could be different. This dependence causes one part of the uncertainties associated with the obtained harmonic coefficients [*Ramillien et al.*, 2004, 2005]. The land water solutions from *Ramillien et al.* [2005] cover the period April/May 2002 to August 2004. They are available as global grids of equivalent water height values with a horizontal resolution of 660 km (corresponding to a spherical harmonic cutoff at degree 30).

2.2. Description of the ORCHIDEE LSM and Its Transfer Scheme

[7] Descriptions of various components of ORCHIDEE are given by *de Rosnay and Polcher* [1998], *Verant et al.* [2004], and *Krinner et al.* [2005]. For the present study, we use water and energy cycle components derived from an earlier version of the model, SECHIBA (Schématisation des Echanges Hydriques à l'Interface entre la Biosphère et l'Atmosphère) developed at the Laboratoire de Météorologie Dynamique (LMD). SECHIBA computes physical processes at the interface between soil, vegetation and atmosphere, water fluxes in the soil and evaporation control by soil moisture [*Ducoudré et al.*, 1993; *de Rosnay and Polcher*, 1998]. Soil hydrology consists of two moisture layers. The upper one has a varying depth. The total soil column has a constant depth of 2 m and a maximum water content of 300 kg/m^3 [*de Rosnay and Polcher*, 1998]. We call ORCHIDEE-1 this model version.

[8] In a second version of the model, called ORCHIDEE-2, we have incorporated a transfer scheme which routes drainage and runoff through three reservoirs that have various residence times. Water in these three reservoirs is not in direct interaction with the atmosphere and progressively flows toward oceans or lakes. Water can flow back into soil moisture reservoirs in endorheic basins and floodplains or through human activities such as irrigation. A major task is to reconcile the resolution of the land surface model, which is imposed by the numerical discretization of the atmosphere, and the higher resolution needed to correctly represent water flow through the landscape.

[9] In ORCHIDEE-2, this is addressed by introducing subgrid basins. A grid cell can cover more than one basin. We define the part of a basin included in a particular grid as a transfer unit, or a subgrid basin. This allows for a number of transfer units within each grid cell. Water from a particular unit can flow to any other unit within the grid or neighboring grids. The disposition of these subgrid basins and their flow directions are computed from a high-resolution global map of basins (here we use the work of *Vörösmarty et al.* [2000], enhanced over the polar regions by *Oki et al.* [1999]). As long as the LSM resolution is coarser than that of the world basins map, this operation can be performed automatically. In order to limit the use of memory and computation, truncation is introduced on the number of subgrid basins. The algorithm reduces the number of transfer units per grid cell by eliminating the smallest basins or removing or those that have the least impact on the direction of outflow from a given grid box (truncation is set to seven in the present study).

[10] Each of subgrid basins retains water in three reservoirs which are characterized by their residence times: the fast, slow, and stream reservoirs. The algorithm linking these reservoirs is relatively simple (Figure 1): runoff is an input into the fast reservoir, drainage is an input to the slow reservoir and all three reservoirs flow into the stream reservoir of the downstream subgrid basin. The flux out of each reservoir is computed using a simple linear relation as proposed by *Singh* [1989].

[11] The flux F_i (kg s^{-1}) out of each reservoir for a transfer unit is given by $F_i = Q_i/(g_i k)$ where Q_i (kg) is water amount in the reservoir i (i = 1, 2, or 3); k (m) is a geometric property of a subgrid basin that depends on the considered reservoir, while g_i is a property of the reservoir (assumed constant over the globe). The estimation of k takes into account the river length d (m) from one subgrid basin to the next subgrid and the height lost over that path Δz (m). The formulation used is based on the work of *Ducharne et al.* [2003] and can be written as $k = \sqrt{\frac{d^3}{\Delta z}}$. The subgrid basin characteristics can be obtained from the maps proposed by *Vörösmarty et al.* [2000]. The reservoir parameters g_i (10^{-3} m^{-1} day) have been estimated empirically using observed discharge of the Senegal River. In this study, g_i have values of 3.0, 25.0, and 0.24 for the fast, slow, and stream reservoirs, respectively. No attempt has been made to define g for other basins although this issue requires further study. Performance of this new transfer scheme has been assessed [*Ngo-Duc et al.*, 2005a]. It was shown that ORCHIDEE reproduces well river discharge over a large number of basins and long time spans, even if the g_i parameter is from a calibration over Senegal River only.

2.3. Numerical Experiments

[12] In stand-alone mode ORCHIDEE requires high-quality forcing data with subdiurnal sampling. These include precipitation, radiation and near-surface temperature, humidity, pressure and wind speed. For this study we have assembled forcing data set for 2002 and 2003 (overlapping the GRACE observations). The precipitation data set is based on the 6-hourly National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kistler et al.*, 2001] constrained by the monthly Climate Prediction Center Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1996]. The other meteorological variables are 6-hourly means for the period

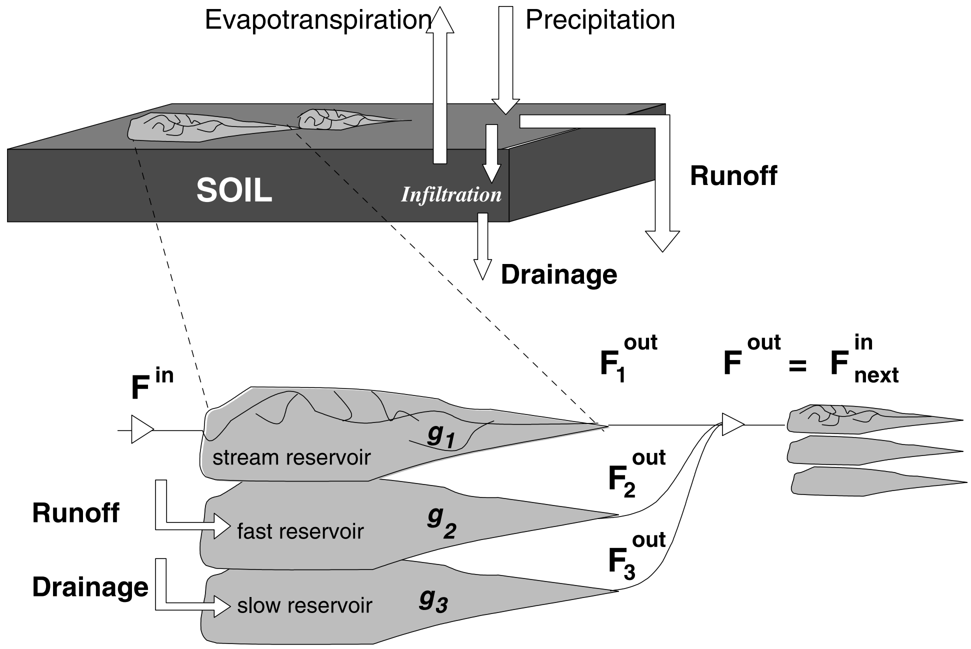

Figure 1. Principle of the transfer scheme. *F* is the flux in or out of each reservoir, and g_i is a reservoir parameter which is assumed to be constant over the globe.

of 1979–2000 from the 53-year (1948–2000) NCC (NCEP/NCAR corrected by CRU (Climate Research Unit)) atmospheric forcing data constructed at the LMD [*Ngo-Duc et al.*, 2005a]. This above strategy was chosen because precipitation variability has much larger impact on the hydrological budget than other meteorological variables [*Ngo-Duc et al.*, 2005a].

[13] In this study two numerical experiments are performed: the first is based on the ORCHIDEE-1 while the second is based on ORCHIDEE-2 (which includes the transfer scheme). Both experiments use the same forcing data as described above.

[14] Outputs of the simulations are processed consistently with the GRACE data: the ($1^\circ \times 1^\circ$) gridded values are transformed into spherical harmonic coefficients up to degree 30, corresponding to a spatial resolution of ~600 km. We exclude the C_{20} coefficient because the early GRACE results exhibit anomalously large variability for this coefficient. The model coefficients are transformed back into a new gridded data set.

3. Results

[15] The GRACE results are compared with the ORCHIDEE simulations without and with the transfer scheme, i.e., ORCHIDEE-1 and ORCHIDEE-2.

[16] Early studies had emphasized the seasonal variability of land water storage based on altimetry data and LSMs [e.g., *Ngo-Duc et al.*, 2005b; *Cazenave et al.*, 2000]. They showed that mean annual land water storage reaches its maximum during February–March–April, while its minimum occurs during August–September–October. Therefore we compared land water storage difference between February–March–April and August–September–October for 2003. This difference simulated by ORCHIDEE-1 (Figure 2b) is clearly smaller than the GRACE-based value (Figure 2a), especially over the largest tropical basins. Taking into account water stored in the three reservoirs of the transfer scheme, as simulated by ORCHIDEE-2 (Figure 2c), leads to improved agreement with the GRACE observations. The observations are particularly well reproduced by ORCHIDEE-2 over the world's largest basins: Amazon, Orinoco, Congo, Niger, Ganges, Mekong and Mississippi. The largest storage is in the third reservoir where drained water has long residence time.

[17] Over high-latitude regions, on the other hand, ORCHIDEE-2 overestimates the water storage difference between the two seasons. This can be explained partly by the fact that snow parameterization is simple. Another likely source of error is the atmospheric forcing used in this study; the forcing temperature has more influence on the water balance simulation over high latitudes than over other regions [*Ngo-Duc et al.*, 2005a]. The assumption, in the simulations, of a constant temperature value over 1979–2000, may cause poor water storage estimates in high-latitude regions.

[18] The temporal correlation of total land water inferred from GRACE and the two versions of ORCHIDEE over their common 20 months period (May 2002 to December 2003) is shown in Figure 3. Figure 3a shows that when the model only stores water as soil moisture and snow, the correlation is weak and not positive in any systematic way. When drained water stored in long residence time reservoirs, the correlation is larger and predominantly positive. This improvement of the model results not only leads to larger signal amplitude as shown above, but also to better phasing compared to the observations. Noticeable areas of disagreement are arid regions (Sahara, Kalahari, central Australia, the south west of North America and Mongolia), where weak signal is present. Further studies are required to improve the ability of the transfer scheme to represent water storage in these areas. Statistically significant regions at the

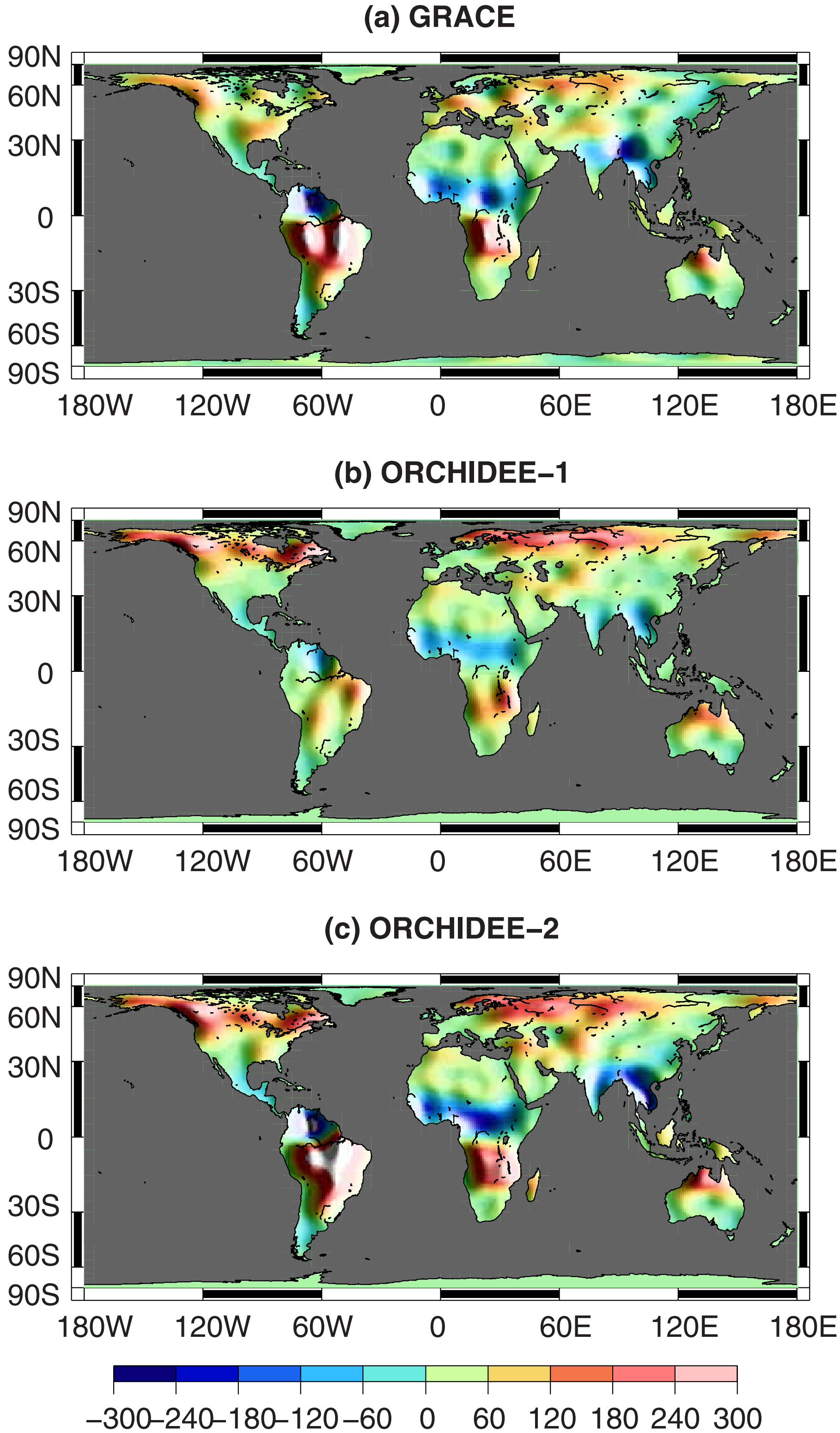

Figure 2. February–March–April minus August–September–October 2003 of total land water (mm) (a) estimated from GRACE, (b) simulated by ORCHIDEE-1, (c) and simulated by ORCHIDEE-2.

95% confidence level are contoured in Figure 3. Assuming a sample size of 20 (number of months), the 95% confidence limit is 0.44. For ORCHIDEE-1 there is little statistical significance except in a small area located in the eastern part of the Mississippi basin and over the Borneo Island (southeast of Asia). With the ORCHIDEE-2 transfer scheme (Figure 3b) many regions appear statistically significant, particularly over the largest world basins.

[19] Time series of mean water storage inferred from the GRACE results (dots), ORCHIDEE-1 (dashed line) and

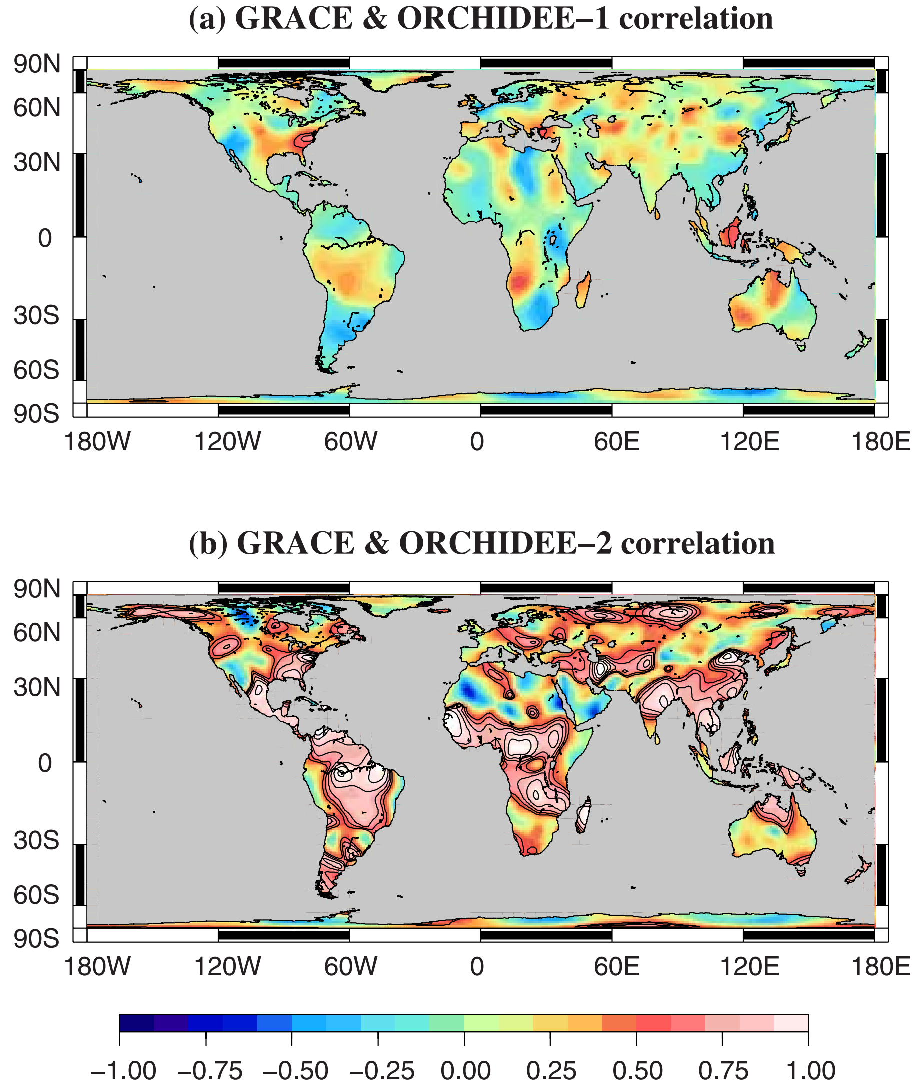

Figure 3. Correlation of total land water inferred from the GRACE results and (a) ORCHIDEE-1 and (b) ORCHIDEE-2. The correlation is calculated for the GRACE data and the ORCHIDEE monthly time series. Statistically significant regions at the 95% confidence level are also contoured (from the statistically significant limit of ~0.483 with an interval of 0.1).

ORCHIDEE-2 (solid line) are presented in Figure 4 for eight tropical basins: Amazon, Congo, Mississippi, Niger, Yangtze, Ganges, Brahmaputra, and Mekong. The error bars associated with the GRACE results in Figure 4 represent only part of the errors. They are calculated from uncertainties associated with the spherical harmonic coefficients of the GRACE geoids [*Ramillien et al.*, 2005]. There are other sources of error that are not taken into account: (1) truncation error (cutoff at degree 30), (2) "masking" error (using a mask to calculate the mean storage of the basins), and (3) "leakage" error (hydrological and other gravitational signals from outside the studied basin can pollute the land water storage estimation). Figure 4 shows that the addition of water storage from drained water in ORCHIDEE-2 improves the comparison with GRACE, both in terms of signal amplitude and phase. The three added reservoirs contribute to at least half the amplitude of the seasonal cycle over most basins. Two exceptions are the Mississippi and Niger basins where the contribution of the soil moisture reservoir is as large as that of drained water.

[20] To provide a more synthetic view of the results, Figure 5 displays a Taylor diagram which shows errors of the simulated water storage for the eight selected tropical basins [*Taylor*, 2001]. A Taylor diagram provides the ratio of standard deviation as a radial distance and the correlation with GRACE results as an angle in the polar plot. White/gray circles correspond to ORCHIDEE-1/ORCHIDEE-2 respectively. The observed basin water storage is represented by a point on the horizontal axis (zero correlation error) at unit distance from the origin (no error in standard deviation). In this representation the linear distance between each model result and observed storage is proportional to the root mean square model error. Figure 5 clearly shows that for the eight selected tropical basins, ORCHIDEE-1 underestimates the variations of water storage, and correlations between ORCHIDEE-1 and GRACE are low. ORCHIDEE-2 better represents the standard deviation, although some overestima-

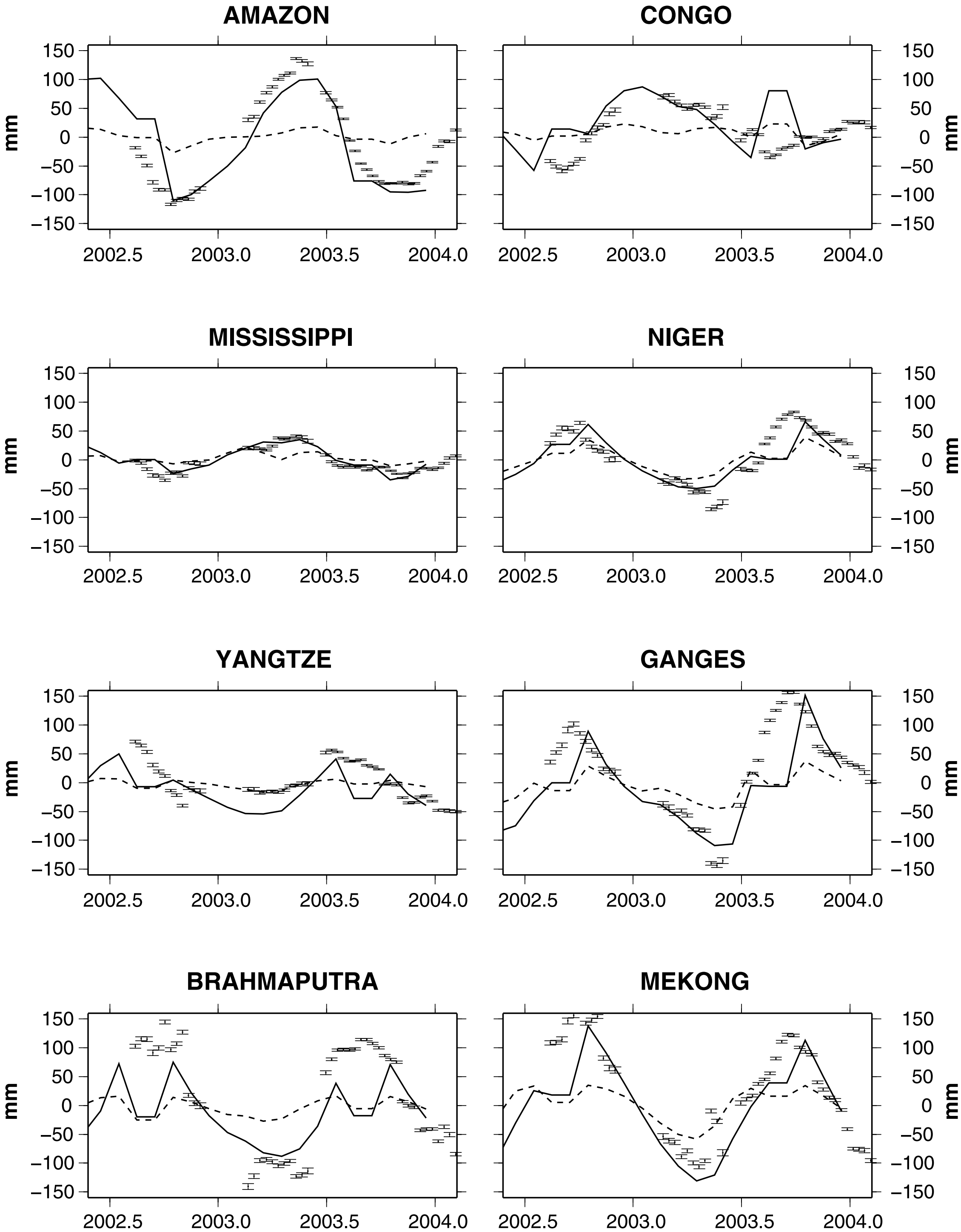

Figure 4. Time series of mean water storage over the eight tropical basins inferred from the GRACE data (dots with the error bars associated) for ORCHIDEE-1 (dashed line) and for ORCHIDEE-2 outputs (solid line).

tion is present (except for the Brahmaputra basin). The inclusion of the three reservoirs improves the correlation between simulated and observed values.

4. Conclusion

[21] The objective of this study is to use GRACE-based land water storage to validate the ORCHIDEE LSM. We show that the revised model which includes a transfer scheme for drained water (ORCHIDEE-2) significantly improves the simulated land water storage, particularly over tropical basins. Over high-latitude regions ORCHIDEE-2 overestimates water storage variations which could be linked to simple snow parameterization or atmospheric forcing uncertainty. The mean water storage time series over the eight tropical basins show that the contribution of

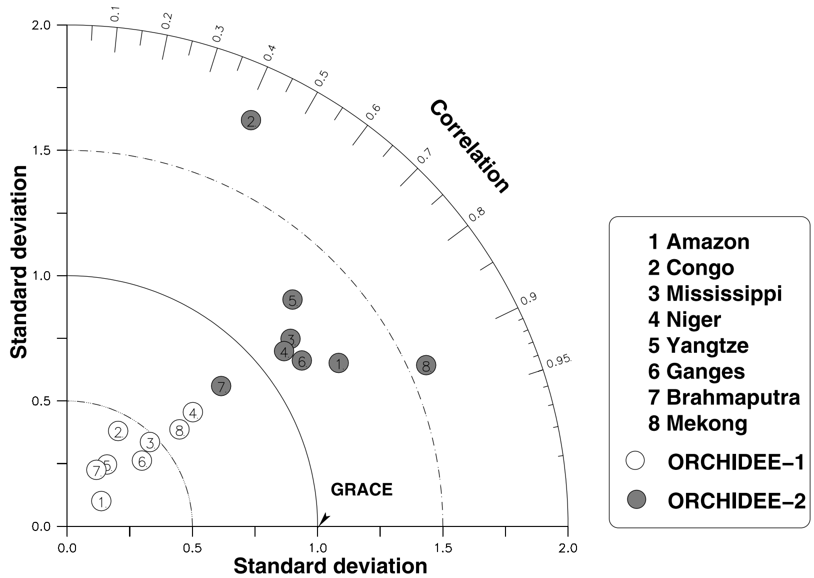

Figure 5. Taylor diagram illustrating the statistics of mean water storage over the eight selected basins simulated by ORCHIDEE-1 (open circles), and ORCHIDEE-2 (shaded circles) as compared with GRACE observations.

the new transfer scheme plays an important role in some basins such as the Amazon, Congo, Yangtze, Ganges, Brahmaputra, and Mekong. These results indicate that the residence time for drained water in ORCHIDEE-2 produces a realistic amount of water storage in continental reservoirs when appropriate time constant is assumed. The better agreement between simulated and observed amplitude and phases suggests that the inclusion of water exchange between continents and oceans might be important for simulating ocean circulation in coupled General Circulation Models (GCMs). For example, the 1997–1998 continental water storage estimate with the LMD GCM has been improved substantially when the transfer scheme was included in the model [*Ngo-Duc et al.*, 2005b]. This was shown by comparing global mean seasonal water storage from the model with the ocean mass component estimated from TOPEX/Poseidon annual mean sea level corrected for thermal expansion.

[22] In the absence of in situ observations at global scale, the use of remote sensing observations of land water storage represents an alternative for improving LSM developed for climate research and water resources studies.

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A. Cazenave and G. Ramillien, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, CNES, 14, avenue Edouard Belin, F-31400 Toulouse, France.

K. Laval and J. Polcher, Laboratoire de Météorologie Dynamique, CNRS, University Pierre et Marie Curie, Case postale 99, 4, place Jussieu, F-75252 Paris Cedex 05, France.

T. Ngo-Duc, Institute of Industrial Science, University of Tokyo, Ce-504, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan. (thanh@rainbow.iis.u-tokyo.ac.jp)