Land water storage from model and space, its effects on global sea level change

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Abstract

The variation of continental storage may have important consequences on water resources. We investigate here its evolution through a 56 year simulation with the Organising Carbon and Hydrology in Dynamic EcosystEms (ORCHIDEE) Land Surface Model (LSM), developed in France. To perform this study, we have built a 56 year atmospheric forcing data set for LSMs based on the NCEP/NCAR reanalysis project and a number of independent in-situ observations. The new data set has a 6-hourly time step from 1948 to 2003 and a spatial resolution of 1°×1°. The outputs of the ORCHIDEE LSM forced by the new forcing are compared to the observed discharges of the world's 10 largest rivers to estimate the combined errors of the forcing data and ORCHIDEE. The quality of forcing data is improved with the integration of the various observations.

The outputs of the ORCHIDEE LSM, driven by the new forcing data set, are used to study land water storage. In comparing with the Gravity Recovery and Climate Experiment (GRACE) data, we show that the predicted land water storage values are quite comparable to the observations, particularly over some large tropical basins such as the Amazon, the Congo, the Ganges, the Mekong, and the Mississippi. Over the last half century, the model shows that no significant trends are detected but there is strong low frequency variability in the land water storage. The contribution of land water to sea level, simulated by ORCHIDEE, is highly anti-correlated with the thermal expansion of the oceans, obtained via global ocean temperature data set. This result indicates that a warming of the oceans accelerates the water cycle and thus contributes to a reduction in the sea level partly compensating the thermal expansion.

Keywords: land water storage, land surface model, atmospheric forcing, GRACE

1. Introduction

Land surface models (LSMs) allow us to estimate the global land surface water and energy cycles. Beside the LSMs, powerful remote sensing instrument have been launched to observe some components of the continental water, carbon and energy budgets. In this study, we aim to use the LSMs' outputs, in-situ observations as well as satellite products to evaluate the time evolving characteristics of the continents.

To improve our understanding and parameterizations of land surface processes, the LSMs have been usually applied in a stand-alone mode. To be used in this mode, a high quality prescribed atmospheric forcing data with a sub-diurnal sampling is required. Before our study [Ngo-Duc et al., 2005b], there were several attempts to produce global atmospheric forcing data sets for use in the land surface modeling community [e.g., Meeson et al., 1995; Hall et al., 2003]. However, all these data sets, which are reanalysis estimates combined with gridded data sets from observations, have too short periods. Therefore, we have constructed a 56-year global atmospheric forcing dataset, which allows for a better study of inter-annual land surface climate variability, and also for application and further development of the methods of calibration, evaluation and validation of LSMs with in situ and remote sensing data. In the next two sections of this paper, we will describe the 56-year forcing data and the validations of the new data by using observed river discharges and by using the products obtained from the Gravity Recovery and Climate Experiment (GRACE) satellite mission.

We will then briefly discuss about the impact of continental water storage on global sea level. Sea level variation is an important consequence of climate change and involves many components of the climate system [Cazenave and Nerem, 2004]. Tide gauge-based observations indicate that over the past 50 years, the rate of the global mean sea level rise was on the order of 1.8 mm/yr [Church et al., 2004]. Up to present, it's still difficult to quantify how much continents contribute to this increasing trend of sea level. The only study to date estimating the latter effect is that of Milly et al. [2003]. Using the Land Dynamics –LaD- LSM, they showed that only 0.12 mm/yr equivalent mean sea level could be attributed to the land water contribution over the last two decades, while significant inter-annual signal was reported. In this study, we extend the estimate of this contribution to the past half century; using the ORCHIDEE LSM developed at the Institute Pierre Simon Laplace (Paris, France) forced by our new 56-year data.

2. 56-year atmospheric forcing data

The input data for LSMs are generally divided into three categories: soils data (fixed in time), vegetation data (some fixed and some monthly varying) and meteorological data (or atmospheric forcing data). The soil and vegetation data are parameter data sets that are used to specify characteristics of the land surface. The meteorological data provide the forcing at the upper boundary of the land surface.

The variables in the meteorological data are divided into two types: state variables (near-surface air temperature, specific humidity, wind speed and surface pressure) and flux fields (radiation and precipitation). We began from the 56-year (1948–2003) pure reanalysis products of NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) [Kistler et al., 2001] then used the observationally based data of the Climate Research Unit (CRU) from University of East Anglia [New et al., 1999, 2000] (for the years before 2000), the monthly Climate Prediction Center Merged Analysis of Precipitation (CMAP) [Xie and Arkin, 1996] (for 2001-2003) and the Surface Radiation Budget (SRB) data produced at NASA Langley Research Center to correct the reanalysis products (see Ngo-Duc et al. [2005b, 2006] for more details). The new forcing data set is named NCC (NCEP/NCAR Corrected by CRU). NCC is a 6-hourly forcing data with a spatial resolution of 1°×1° for the period of 1948–2003.

To facilitate the exchange of forcing data for LSMs and the results produced by these models, the Global Energy and Water Cycle Experiment (GEWEX) Global Land Atmosphere System Study (GLASS) established the Assistance for Land surface Modeling activities (ALMA) convention for LSM input and output variables (http://www.lmd.jussieu.fr/ALMA/). The aim is to have a data exchange format which is stable but still general and flexible enough to evolve with the needs of LSMs. NCC data were thus saved using the ALMA convention. The data are currently available at ftp://hydro.iis.u-tokyo.ac.jp/pub/thanh/NCC/

3. Model Description and Experimental Design

The descriptions of the various components of ORCHIDEE can be found in De Rosnay and Polcher [1998], Verant et al. [2004] and Krinner et al. [2005]. For this study, we have only used its water and energy cycle component. ORCHIDEE computes the physical processes at the interface between soil, vegetation and atmosphere, the water fluxes in the soil and the control of evaporation by soil moisture [Ducoudré et al., 1993; De Rosnay and Polcher, 1998]. In the model, the soil hydrology consists of two moisture layers with the upper one having a varying depth. The total soil depth is constant at 2 m and the soil has a maximum water content of 300 kg/m^3.

Runoff occurs when the soil is saturated and it is the only runoff mechanism in the model. A development of the model is to include a routing scheme, which uses a map of the world basins built by combining the map built by Vörösmarty et al. [2000] and the one built by Oki et al. [1999]. At each time step, runoff and drainage fluxes are temporarily stored in three reservoirs which have different residence time constants: the fast, the slow and the stream reservoir. The algorithm linking these reservoirs is relatively simple: 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 grid. The water is progressively routed to the oceans, following the main slopes and taking into account the tortuous path of the river channels, through a cascade of linear reservoirs.

Two numerical experiments are performed in this study: ORCHIDEE LSM forced (1) by the NCEP/NCAR reanalysis products (hereafter called NCEP/NCAR experiment) and (2) by the new NCC data set described in section 2 (NCC experiment).

4. River discharge, comparison with in-situ observations

As most variables describing the state of the surface are not directly observable, to assess the quality of the ORCHIDEE LSM, we take advantage of the integrated routing scheme which allows us to compare the simulated and the observed discharge over the river basins. River discharge is an appropriate observable measure to validate the large-scale water balance. The river discharge measurements used here are the data set provided by the Global Runoff Data Center (GRDC: http://www.grdc.sr.unh.edu/) and by the University of Corporation for Atmospheric Research (UCAR: http://dss.ucar.edu/datasets/ds552.1/). When the simulated river discharges and the observations are compared, only the period overlap is used to compute statistics.

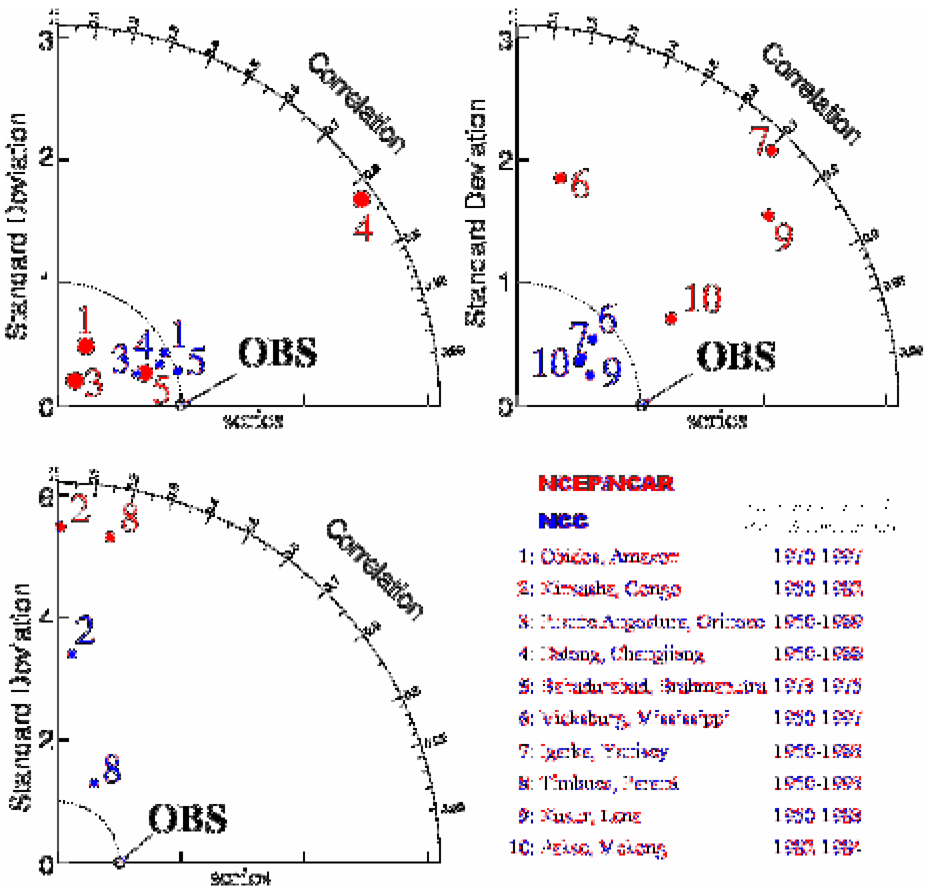

Figure 1: Taylor diagram illustrating the statistics of 10 largest rivers discharges simulated by NCEP/NCAR and NCC experiments compared against the observations for the whole common (observation and simulation) period. Note the different axis scales between the plot that represents two stations Kinsasha and Timbues and the two other plots.

Figure 1 displays a Taylor diagram [Taylor, 2001], which shows the error in the simulated discharge for the full time series. The Taylor diagrams provide the ratio of standard deviation as a radial distance and the correlation with observations as an angle in the polar plot. Consequently, the observed discharge is represented by a point on the horizontal axis (zero correlation error) and at unit distance from the origin (no error in standard deviation). In this coordinate system, the linear distance between each experiment's point and the ''observed'' point is proportional to the root mean square model error.

Figure 1 illustrates the statistics of the world's 10 largest river discharges (by the estimated river mouth flow rate) simulated by NCEP/NCAR and NCC for the overlapping period of the simulations and the observations at the 10 stations closest to the mouth of these rivers. For all the basins, **Figure 1**

shows very clearly that NCC has better quality than NCEP/NCAR. The simulated discharges of the Amazon, the Changjiang, and the Brahmaputra are quite realistic; their correlations with the observations vary from 0.9 to 0.95 and their normalized standard deviations are very close to 1.

5. Land water storage, comparison with GRACE

Launched in mid-March 2002, the GRACE mission, developed by the National Aeronautics and Space Administration in the United States and the Deutsches zentrum fur Luft and Raumfahrt in Germany, provides time variable geoid observations, which -over continental areas- are closely related to changes in vertically integrated terrestrial water storage. Recent studies have demonstrated the ability of GRACE to monitor water storage variability on continental areas with a resolution of ~ 500 km and a precision of a few cm in water thickness [eg.,Wahr et al., 2004; Ramillien et al., 2005; Swenson and Milly, 2006, Ngo-Duc et al., 2006]. It was showed that the water mass changes over the continents observed by GRACE correspond well to those predicted by the hydrology models. Thus in the present study, we would like to use GRACE as a tool for validating the land water balances simulated by our NCC experiment.

The GRACE Project releases gravity field solutions on a monthly basis since April 2002. 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 ≤ 120. Subscript n and m are degree and order of the spherical harmonic expansion. The gravity variations that GRACE can detect include vertically integrated changes in different reservoirs: changes as a result of surface and deep currents in the oceans; changes in the distribution of water and snow stored on land; mass changes of the ice sheets and glaciers; air and water vapour mass change within the atmosphere; and variations of mass inside the solid Earth. In this study, we use the GRACE land water solutions computed by Ramillien et al. [2005], using a generalized least-squares inversion. To constrain the inversion, independent information derived from outputs of the global atmospheric, hydrological and oceanic models was included. The land water solutions from Ramillien et al. [2005] cover the period April/May 2002 to August 2004.

The outputs of the NCC simulation are processed in the same manner as the GRACE data. They were converted from their native grid (1°×1°) to a set of spherical harmonic coefficients. Only the same set of coefficients with the GRACE data are used. Because noise in the GRACE data becomes critical for higher degrees, the comparison will use the spherical harmonic coefficients up to degree/order 30, corresponding to a spatial resolution of ~600 km. We exclude also the C_{20} coefficient because the GRACE results exhibit anomalously large variability in the first few months.

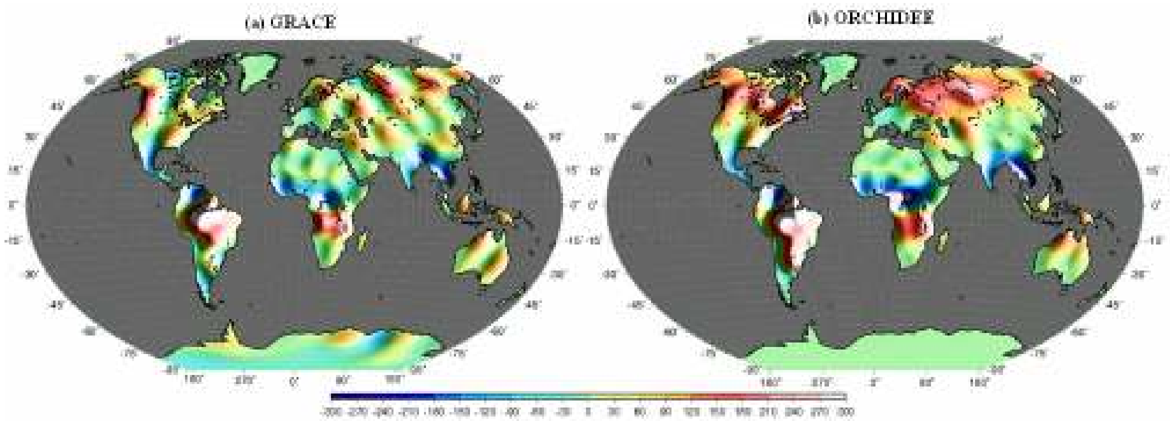

Figure 2: Global seasonal variations of the total land waters (April/May minus November 2002), (a) estimated from inversion of the GRACE geoids, (b) simulated by ORCHIDEE. Units in mm.

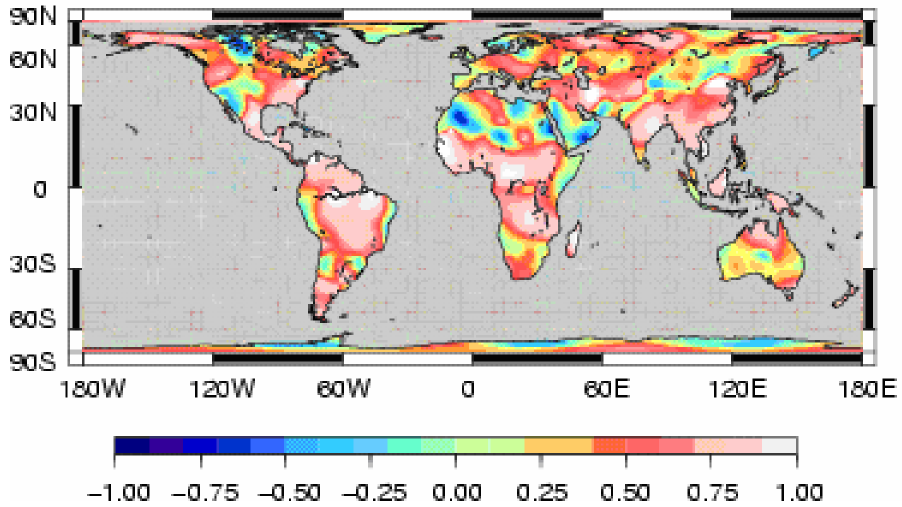

Figure 3: Correlation of the total land water inferred from the GRACE data and the NCC experiment. The correlation is calculated for the whole common monthly time series of 2002 and 2003 between the GRACE data and NCC.

Figure 2 shows an estimation of the amplitude of the seasonal cycle (April/May 2002 minus November 2002) of land water storage inferred from the GRACE data and the NCC experiment. **Figure 3** shows the temporal correlation of the total land water inferred from GRACE and the model over their common period during 2002 and 2003. From the 2 figures, we can conclude that the GRACE observations are generally well reproduced by the model, particularly over the world's largest basins: Amazon, Orinoco, Congo, Niger, Ganges, Mekong and Mississippi. Over high latitude regions the NCC experiment overestimates the water storage. This can be explained in part by the fact that the snow parameterization in the ORCHIDEE LSM is rather simple. Another likely source of error is the atmospheric forcing used in this study. As discussed in Ngo-Duc et al. [2005b], the forcing temperature has more influence on the water balance simulation over the high latitudes than over other regions. In the NCC forcing data, we used a mean temperature from 1979 to 2000 for the years 2001-2003 [Ngo-Duc et al., 2006]. This may cause the differences in high latitudes.

6. Land water storage, effects on sea level change

In the previous sections, we have shown that the NCC experiment can simulate well the water balance at local/regional scale (river discharge) as well as at global scale (land water storage in comparison with GRACE). Those results give us some confidence in the quality of our water storage simulation. In this section, with help of NCC, we will investigate impact of continental water budget on global sea level (see Ngo-Duc et al. [2005c] for more details). The only study to date estimating this effect is that of Milly et al. [2003]; using the LaD LSM, they showed that only 0.12 mm/yr equivalent mean sea level could be attributed to the land water contribution over the last two decades, while significant inter-annual signal was reported.

Figure 4 shows that for the past 50 years, there is no significant trend but strong low frequency variability in the contribution of land water storage to sea level. We note a strong decrease in the beginning of 1970s, followed by a slow increase during the following 20 years. The greatest variation is associated with the ground water (the water in the river systems and in the aquifers simulated by ORCHIDEE from runoff and drainage), followed by soil moisture. In the model, snow does not contribute significantly to this inter-annual variation. In **Figure 4** is superimposed the land water storage contribution from Milly et al. [2003] for the last two decades. Over their period of overlap (1981-1998), LaD and ORCHIDEE models provide small positive sea level trends of 0.12 mm/yr and 0.08 mm/yr respectively. Both models display similar inter-annual/decadal variability except for 1993 when ORCHIDEE displays a downward trend, not seen in the LaD simulation.

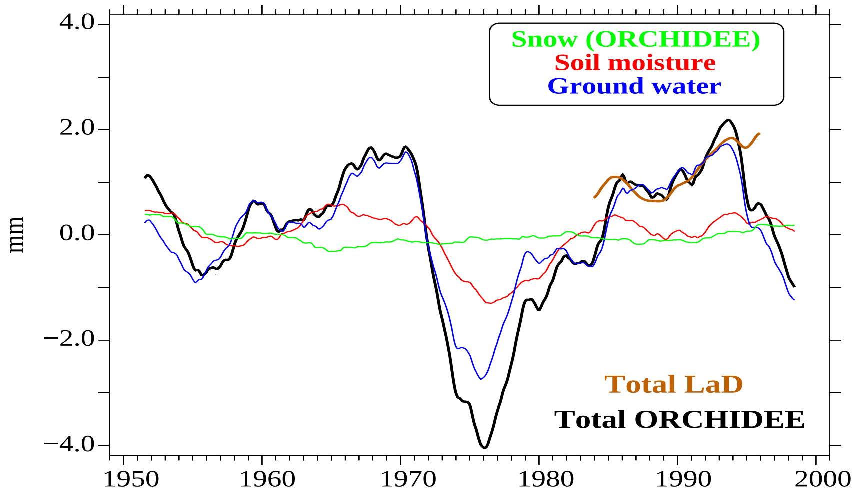

Figure 4: 5-year moving average time series of water reservoirs changes expressed as equivalent global sea level anomalies for the past 50 years. Red curve: soil moisture; green curve: snow pack; blue curve: ground water; black curve: sum of the above components, which represents the land water storage variations simulated by the ORCHIDEE model. Brown curve: land water storage variations simulated by the LaD model.

Figure 5 shows the land water storage contribution estimated by NCC and the thermosteric (i.e., due to thermal expansion) sea level curve, for the past 50 years. The thermosteric sea level was computed by Lombard et al. [2005] using the global ocean temperature (down to 500 m) data set from Levitus et al. [2005], covering the period 1955-2003. Since there is no significant trend in the land water storage contribution (**Figure 1**, **Figure 4**), we have removed the trend in the thermosteric signal in order to make **Figure 5** more readable.

A clear negative correlation appears in **Figure 5** between thermosteric sea level and the land water contribution, at decadal/inter-decadal time scales. For the overlapping period, the correlation is -0.84.

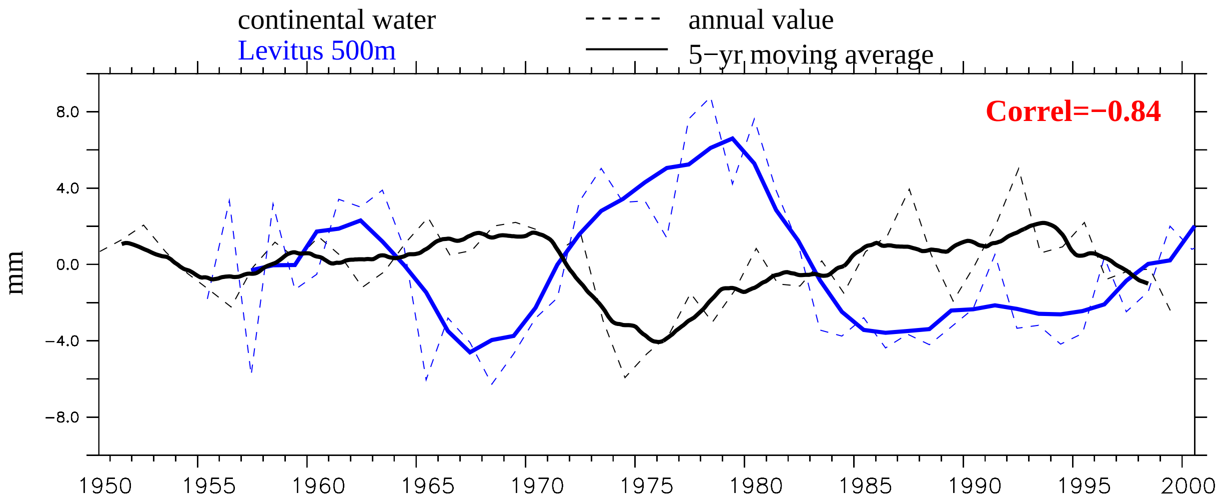

Figure 5: Time series of changes expressed as equivalent global sea level anomalies (mm) for the past 50 years. Black curve: land water simulated by the ORCHIDEE LSM forced by the NCC forcing data; blue curve: Levitus thermosteric down to 500 m [Levitus et al., 2005].

As the thermosteric sea level closely follows the variations of the ocean heat content [e.g., Levitus et al., 2005], increasing thermosteric sea level correspond to ocean warming. To explain the anti-correlation between thermosteric sea level and land water storage fluctuations, we propose the following hypothesis: As ocean temperature rises, evaporation increases; hence more precipitation over the oceans and land occurs. An increase in precipitation will lead to more water stored on the continents, leading to a negative feedback on sea level. Warming of the oceans thus influences the water cycle, leading to increased storage of water on continents, which in turn partly compensates thermal expansion contribution to sea level change.

7. Summary and Conclusions

In this paper, we have presented the construction of a 56 year atmospheric forcing data set for LSMs with helps of the NCEP/NCAR reanalysis and a number of independent observations. The resulting data set, called NCC, has been used as input for the ORCHIDEE LSM. The observed discharges of the world's 10 largest rivers were used to compare with the simulation. We have also used the GRACE satellite data to validate the land water storage obtained with ORCHIDEE. The model represents well the water storage, particularly over the tropical largest basins. Over some regions in the high latitudes, ORCHIDEE overestimates the water storage variations, which could be linked to the simplistic snow parameterization or the input atmospheric forcing uncertainties.

The NCC atmospheric forcing data set is very helpful because of its global coverage and its long period. We have used NCC to estimate the contribution of land water storage to the sea level change. We show that, over the last half century, the contribution of land water storage to sea level has no significant trend but displays strong decadal variability. We also report a high negative correlation between the contribution of land water to sea level and thermal expansion of the oceans, suggesting that change in ocean heat content has significant influence on the global hydrological cycle. Our result also indicates that, at decadal time scales, there is partial compensation between thermal expansion and land water contribution to sea level.

8. References

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