Evaluating land water storage in the GSWP-2 simulations

T. Ngo-Duc[1], N. Hanasaki[1], T. Oki[1], K. Laval[2], A.Lombard[3]
[1]*Institute of Industrial Science, University of Tokyo, Japan;*
[2]*Laboratoire de Meteorologie Dynamique, University of Paris VI, France*
[3]*Laboratoire d'Etude en Géophysique et Océanographie Spatiales, CNES, France*
thanh@rainbow.iis.u-tokyo.ac.jp

Abstract

The second Global Soil Wetness Project (GSWP2) is an initiative to compare and evaluate 10-year (1986-1995) simulations by a broad range of Land Surface Models (LSMs) under controlled conditions. Simulations by 13 LSMs from five nations have been performed in "offline mode" (i.e. prescribed atmospheric conditions) to provide global estimates of land states and fluxes at a 1°×1° resolution, spanning the years 1986-1995. The runoff and drainage fields given by the GSWP-2 simulations are routed to the oceans by the Total Runoff Integrating Pathways (TRIP) model. In this analysis, we present an evaluation of the GSWP2 land water storage, i.e. sum of soil moisture, snow and water in the river channels. We show that the land water storage variations given by the different GSWP2 simulations are in good agreement in phase as well as in amplitude. They well represent the Topex/Poseidon altimetry derived data. In this study, we also examine the relationship between the simulated land water storage and the thermal expansion of the oceans, obtained via global ocean temperature data set. At inter-annual timescale, these two quantities are highly anti-correlated before 1991 and have a positive correlation from 1991 afterward. The hypothesis: "warmer oceans, wetter continents" proposed by Ngo-Duc et al. [2005c] has not been validated yet.

Keywords: land water storage, routing scheme, Topex/Poseidon, GSWP2

1. Introduction

The second Global Soil Wetness Project (GSWP2) [International GEWEX Project Office, 2002 ; Dirmeyer et al., 2006] is an ongoing environmental modeling research activity aiming at producing global estimates of soil moisture, temperature, snow water equivalent, and surface fluxes by integrating one-way uncoupled Land Surface Models (LSMs) using externally specified surface forcing and standardized soil vegetation distributions. As of May 2005, 15 institutes from five nations have submitted their baseline run, and model ensemble mean (or simple arithmetic average of outputs among models) of surface fluxes and state variable have been produced using 13 models [Dirmeyer et al., 2006]. Gao and Dirmeyer [2006] compared the products (GSWP2-Multi Model Analysis, hereafter GSWP2-MMA) with in-situ soil moisture observation from the Global Soil Moisture Data Bank [Robock et al., 2002] and found that GSWP2-MMA is better than the best individual model at any location in the representation of both soil wetness and its anomaly.

A number of previous studies have shown that, at the annual frequency, the global mean sea level, as measured by Topex/Poseidon (T/P) altimetry, results from two main contributions: thermal expansion of the oceans and water mass exchanged with other reservoirs (atmosphere, land water reservoirs, and ice caps) [eg, Cazenave et al., 2000; Ngo-Duc et al., 2005a]. These studies showed that residual signal from T/P, thermal expansion (given by global subsurface sea temperature data) and water vapor (given by reanalysis data) gave thus an image about the water storage over the continents and could be used to compare with/validate outputs of LSMs. Ngo-Duc et al. [2005a] studied the water storage variations during the major 1997-1998 El Niño- Southern Oscillation (ENSO) events and showed that the drastic amplitude change of land water storage observed from T/P satellite altimetry was represented in their GCM simulation. However, large differences still remain in the amplitude of the simulation and the observation. At longer frequency, such as decadal/multi-decadal variations, Ngo-Duc et al. [2005c] studied the relationship between land water storage and thermosteric sea level variations. They showed a high anti-correlation between the two quantities and proposed then a hypothesis: warming of the oceans thus influences the water cycle, leading to increased storage of water on continents, which in turn partly compensates for the thermal expansion contribution to sea level changes.

In this study, we use similar approaches as the above studies to see if the GSWP2-MMA product, supposed to have better quality than GCM simulation and individual off-line simulation, can represent well the derived T/P observations. Also, the relationship between land water-based and thermosteric sea level fluctuations, mentioned in Ngo-Duc et al. [2005c], is also evaluated. Because of the relatively short time period of the GSWP2 simulations (1986-1995), we focus on seasonal and inter-annual timescales.

2. Numerical experiments

The GSWP2-MMA data, as well as the data submitted by the participating modeling groups (BUCK, CLM2-TOP, HYSSiB, ISBA, LaD, MosaicLIS, MOSE2, NOAH, NSIPP-CATCHEMENT, ORCHIDEE, SSiBCOLA, SiBUC, SWAP, VISA) (see Dirmeyer et al. [2006] for more details) conforms to the Assistance for Land-surface Modelling Activities convention (ALMA) [Polcher et al., 2000]. The data has 1° by 1° (longitude-latitude) spatial resolution, and daily temporal resolution spanning the years 1986-1995. All models (and GSWP2-MMA) provide two runoff variables: surface runoff and subsurface runoff. The partition of runoff into surface and subsurface varies significantly between models. In this study, the total runoff, or simple summation of surface and subsurface is used as input for the Total Runoff Integrating Pathways model (TRIP; Oki and Sud [1998]). TRIP is a global river routing model which can help to isolate the river basins, inter-basin translation of water through river channels, as well as collect and route runoff to the river mouth(s) for all the major rivers. For each simulation (TRIP driven by the runoff field of each LSM and of GSWP2-MMA), two output variables of TRIP, river discharge (m^3/s) and river storage (kg) on a digital river network map with a spatial resolution of 1° longitude by 1° latitude, are saved. Water storage over land is defined by the sum of soil moisture, snow depth (from the 13 LSMs and GSWP2-MMA) and river storage generated by TRIP.

3. Comparison between simulated land water storage and satellite derived data

3.1. Land water storage inferred from T/P and other data sets

Ngo-Duc et al. [2005a] studied the water storage variations during the major 1997-1998 ENSO events and showed that the drastic amplitude change of land water storage observed from T/P was represented in their GCM simulation. However, large differences still remain in the amplitude of the simulation and the observation.

In this section, we aim to evaluate if the GSWP2-MMA product, supposed to have better quality than GCM simulation and individual off-line simulation, can represent well the T/P derived data. We focus on the 3 years: 1993, 1994, and 1995 because this is the overlapping period for the observed data and the simulations.

Topex/Poseidon data: T/P altimetry data for 1993-2002 are analyzed to estimate the variations of the global mean sea level. The altimeter products were produced and distributed by AVISO [source: http://www.aviso.oceanobs.com]. The inverted barometer correction associated with the instantaneous local response of sea level to atmospheric pressure variations has been applied as explained by Minster et al. [1999]. To estimate the seasonal signal from January 1993 to December 1995, the sea level time series have been detrended (Figure 1, red curve). The positive trend, amounting to 3 mm yr^{-1} over the 1993–2002, mostly results from warming of the oceans plus mountain glacier and ice sheets melting [Cazenave and Nerem, 2004].

Ocean Temperature data: To correct for thermal expansion (also called steric or thermosteric effect), we used historical data of ocean subsurface temperature made recently available by Ishii et al. [2005]. This data set consists of monthly 1° by 1° gridded ocean temperatures and associated uncertainties, down to 700 m (16 depth layers) for 1945–2003. To estimate the steric sea level for a given month, we computed density change with respect to a reference density at any level and grid point according to the classical expression in which the density is obtained in a sequence of steps [Gill, 1982; see also Lombard et al., 2006] (Figure 1, green curve).

As discussed in previous studies, the residual signal (T/P minus steric effect) represents water mass changes inside the oceans which are related to water mass changes in the atmosphere and the terrestrial reservoirs according to the water mass conservation equation [e.g., Minster et al., 1999]:

$$\Delta M_{Oceans} + \Delta M_{WaterVapor} + \Delta M_{LandWaterStorage} = 0 \qquad (1)$$

where ΔM is the water mass change inside each of the three main reservoirs: oceans, atmosphere, and continents.

Water vapor variations: To estimate the water vapor contribution, we used water vapor distribution estimated based on the 50-year National Center for Environmental Prediction/National Centers for Atmospheric Research (NCEP/NCAR) reanalysis [Kistler et al., 2001].

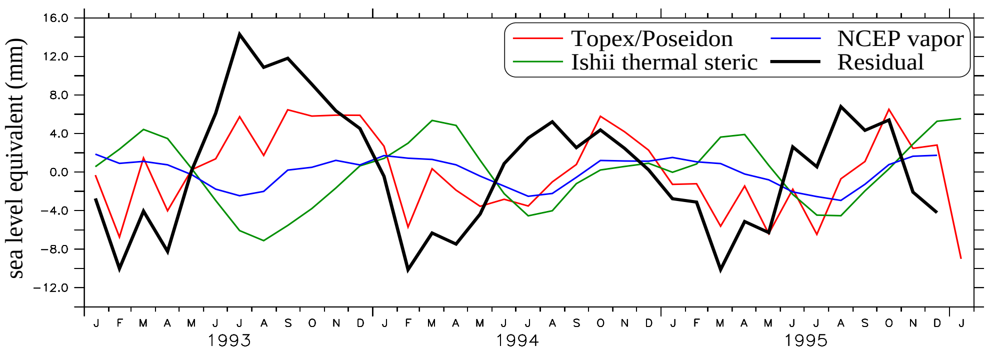

Figure 1: Sea level observed by T/P (red curve). Steric sea level estimated from Ishii [2005] (green curve). Water vapor (expressed in equivalent sea level) estimated from NCEP/NCAR reanalysis (blue curve). Residual signal (T/P minus steric effect minus water vapor) is represented by the thick black curve.

Figure 1 shows detrended T/P sea level, steric effect and water vapor in terms of equivalent sea level. The residual signal (black curve), according to equation 1, represents the water storage variations over land. This signal (hereafter OBS) can be compared with the simulated values. However, before using OBS, one should note that OBS may contain some uncertainties due to: (1) errors associated with the measures of T/P, the steric effect, the water vapor contribution; (2) missing signal in the high-latitude oceans because the T/P satellite covers only the area between 66N and 66S. Figure 1 shows in particular that while the observed annual mean sea level has an amplitude of about 6 mm, correcting for thermal expansion (amplitude of about 4 mm) and atmospheric water vapor (amplitude of 2 mm) gives a residual amplitude signal (OBS) varies from about 8-12 mm. This is so because the two contributions steric and vapor are almost out of phase compared to the observed annual sea level. The OBS signal shows clear inter-annual variations for the 3 years 1993, 1994, 1995, especially the drastic amplitude change between 1993 and 1994.

3.2. GSWP2 simulations and OBS

The soil moisture, snow contents and water stocked in the river channels, which constitute the water storage over continents, are estimated through the GSWP2 simulations. The exchange of land water storage (Antarctica is neglected in the model) to other reservoirs is calculated in equivalent sea level variations via a multiplicative factor f :

$$f = -\frac{S_{continents}}{S_{ocenas}} \qquad (2)$$

where $S_{continents} = 1.343 \times 10^{8}$ km^2 and $S_{oceans} = 3.625 \times 10^{8}$ km^2 (obtained from World Atlas).

Figure 2 shows the land water storage variations simulated by the models that participated in the GSWP2 project. We don't present NOAH and VISA curves because their values are too different from other simulations. The LaD curve is also not shown because soil moisture is not provided by LaD. OBS is also shown in this figure.

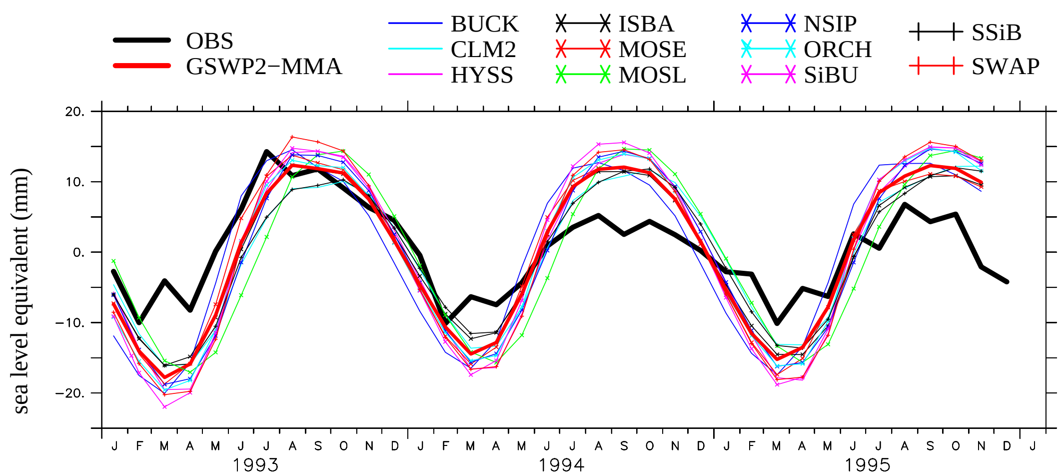

Figure 2: Contributions of land water (snow, soil moisture, and river storage) to sea level variations simulated by the GSWP2 models, GSWP2-MMA (thick red curve) and given from the observations (OBS, black curve).

Figure 2 shows that the land storage variations simulated by the 11 different LSMs and by GSWP2-MMA are in good agreement in phase as well as in amplitude. The simulated values are also in phase with OBS. However, they don't show a clear inter-annual variability as OBS does. The difference can be explained by the uncertainties in OBS discussed above, and by the uncertainties in the simulations, for example: errors associated with the atmospheric forcing data set used by the GSWP2 models; and that Antarctica is not taken into account in the models. Another reason can be that artificial reservoirs have not been taken into account yet. Artificial reservoirs are estimated to have 8,000 km^3 of capacity, and it should correspond to approximately 20 mm of sea level decrease, if all the reservoirs are filled up [Hanasaki et al., 2006].

We realize that OBS and the simulated land water variations (expressed in equivalent sea level) are strongly anti-correlated with the thermosteric signal, at seasonal scale (see Figure 1 and Figure 2). The thermosteric contribution reaches its maximum in March because of the increase of ocean temperature in the Southern Hemisphere (Figure 3.a). Meanwhile, much water is stored over land due to snow over high latitude regions and due to high soil moisture and much water in the river channels in the Southern Hemisphere, which originate from the intensification of rainfall during March (Figure 3.b and 3.c).

Therefore, at seasonal scale, warmer oceans coincide with wetter continents.

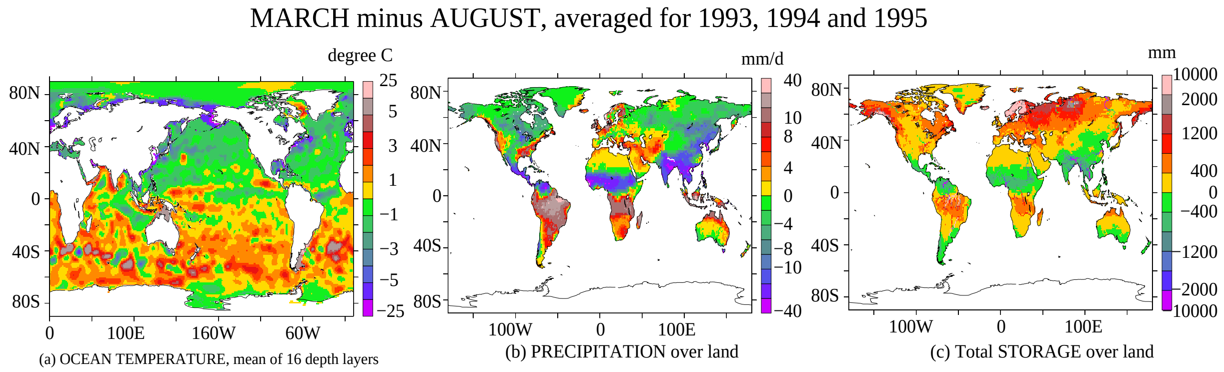

Figure 3: Difference of March and August values, averaged for 3 years 1993, 1994 and 1995: (a) ocean temperature averaged from 16 different depth layers (from 0 m to 700m of depth) mean of (b) Input land Precipitation for the GSWP2 simulation (c) Total storage over land simulated by GSWP2-MMA.

4. Variability of GSWP2 water storage over the period of 1986-1995

Ngo-Duc et al. [2005c] studied the relationship between land water-based and thermosteric sea level fluctuations at decadal/multidecadal time scales for the period of 1950-2000. They compared the land water storage simulated by the Organising Carbon and Hydrology in Dynamic EcosystEms (ORCHIDEE) LSM to the thermal expansion of the ocean and reported a high negative correlation. Ngo-Duc et al. then proposed a hypothesis: an increase in ocean heat will lead to more water being stored on the continents, leading to a negative feedback on the sea level.

We would like to examine here the above hypothesis with the GSWP2 simulations. We will look at the inter-annual timescale because of the relatively short period of the GSWP2 runs (1986-1995).

Figure 5 represents the inter-annual anomalies of land water storage for the different LSMs that participated in GSWP2. The thermosteric sea level obtained from Ishii et al. [2005] is superimposed (black thick curve). In general, the models show the same inter-annual variability. The high values in 1986 may be caused by too high forcing radiation in the spin-up calculation period (1982-1985) [K. Yorozu, personal communication]. Due to overestimation of input (downward) radiation, the simulated evaporation until 31 Dec 1985 is large and suddenly decreases from 1 Jan 1986. This problem can contribute to the sudden decrease of land water contribution to sea level in 1986.

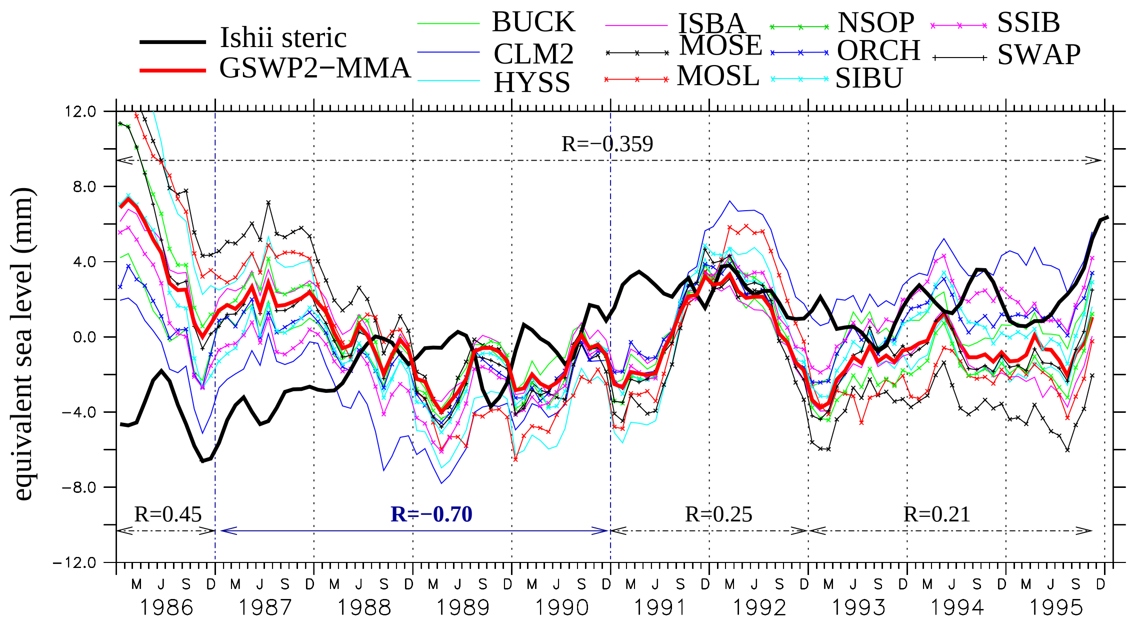

Figure 5: Inter-annual anomalies (global signal minus mean seasonal cycle) of land water storage given by the GSWP2 simulations, expressed in terms of equivalent sea level. The thermosteric sea level obtained from Ishii et al. [2005] and its correlations with GSWP2-MMA signal for different periods are also shown.

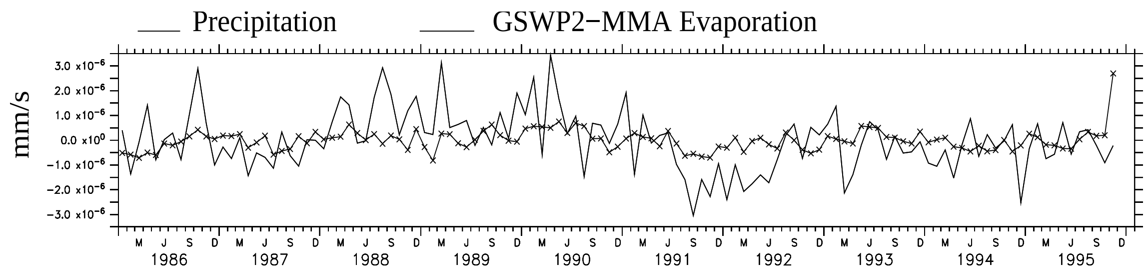

Figure 6: Input precipitation of GSWP2 simulations and evaporation given by GSWP2-MMA, inter-annual anomalies (global signal minus mean seasonal cycle) averaged over the whole continents.

One may question the reality of the inter-annual signal of the GSWP2 water storage outputs. We can get some indirect answers by comparing the discharges of some major rivers with the observations. Here we show just a case study for the world's largest river: Amazon. The inter-annual river discharge computed by the GSWP2 models at Obidos (1.95°S, 55.51°W; the station closest to the mouth of the Amazon river) is compared with the observations of the HYBAM (Hydrogeodynamique du Bassin Amazonien) group [Callède et al., 2004] (see Figure 7). The GSWP2 models reproduce well the inter-annual signal of the Amazon discharge. For example, the floods of 1986 and 1989, and the drought of 1992 over the Amazon are well represented by the models. Figure 7 gives us some confidence in the quality of the GSWP2 outputs.

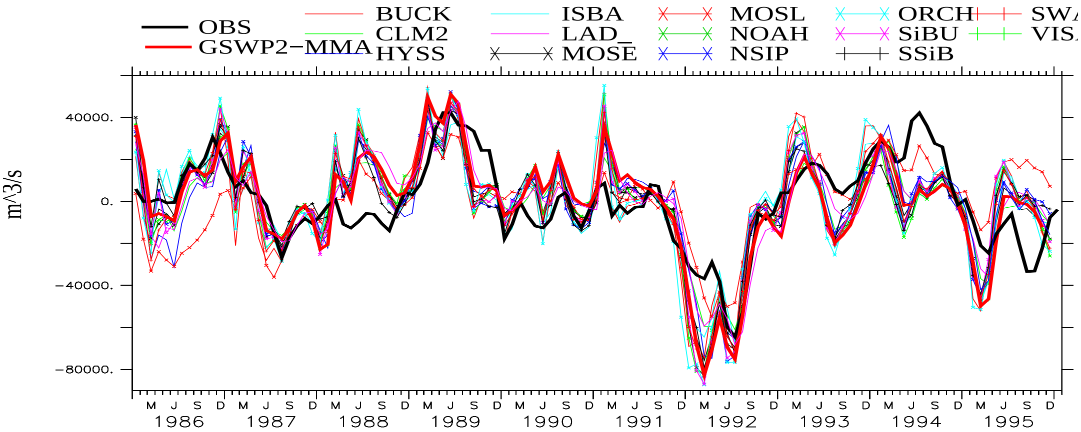

Figure 7: Annual discharge anomaly at the Obidos station over the Amazon simulated by the GSWP2-models (GSWP2-MMA is represented by the red thick curve). The observation is the black thick curve.

Going back to Figure 5, we examine the relationship between land water storage and thermosteric sea level. For the whole period of 1986-1995, a negative correlation of about -0.359 is obtained. The positive correlation in 1986 seems to be unrealistic because 1986's land water is highly affected by the sudden change of the input radiation as discussed above. From January 1987 to December 1990, high negative correlation (-0.70) is obtained which confirms the hypothesis of Ngo-Duc et al. [2005c] for this period: warmer oceans, wetter continents. However, we don't have the same relationship from 1991 afterward. A big decrease of land precipitation during 1991 and 1992 (Figure 6) led to less water stored on the continents, i.e. the continents lost water to the oceans. The correlation between land water storage and thermosteric sea level is positive (0.25 for 1991-1992, 0.21 for 1993-1995). Thus, the hypothesis proposed by Ngo-Duc et al. [2005c] has not been validated for the years after 1991.

From this point, some questions arise: why are there such differences in the relationship between land water storage and thermosteric effect before and after 1991? Is the high negative correlation from January 1987 to December 1990 just a coincidence? Are land water and thermosteric effect really anti-correlated? In a further study, we will seek answers to these interesting questions.

5. Summary and Conclusions

We have shown that the land water storage variations simulated by the different GSWP2 LSMs are in good agreement in phase as well as in amplitude. They also represent the phase of land water storage derived from the T/P altimetry data. At seasonal timescale, the land water storage contribution to sea level varies in opposite phase with the thermosteric effect. At inter-annual timescale, these two quantities are highly anti-correlated before 1991 (1987-1991) and have a positive correlation from 1991 afterward. At this state of the study, the hypothesis proposed by Ngo-Duc et al. [2005c] has not been validated for inter-annual timescale. More detailed analysis should be done in further studies. Also, evaluating the role of artificial reservoirs [Hanasaki et al., 2006], which have not been taken into account in this study, could be an interesting issue in order to understand the current differences between the models and the derived observation data.

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