GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L09704, doi:10.1029/2005GL022719, 2005

Effects of land water storage on global mean sea level over the past half century

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Received 15 February 2005; revised 31 March 2005; accepted 13 April 2005; published 12 May 2005.

[1] The output of the ORCHIDEE Land Surface Model, driven by a 53-yr (1948–2000) atmospheric forcing data set, was used to estimate the effects of land water storage on global mean sea level. Over the past half century, no significant trend was detected but there is a strong decadal variability in the land water storage, driven by precipitation and originating principally in the tropics. The land water contribution to sea level change over the past 50 yr appears highly anti-correlated with thermal expansion of the oceans. This result suggests that change in ocean heat content influences the global water cycle. It also shows that, at decadal time scale, there is partial compensation in sea level changes between thermal expansion and ocean water mass change due to changes in land water storage. **Citation:** Ngo-Duc, T., K. Laval, J. Polcher, A. Lombard, and A. Cazenave (2005), Effects of land water storage on global mean sea level over the past half century, *Geophys. Res. Lett.*, *32*, L09704, doi:10.1029/2005GL022719.

1. Introduction

[2] Sea-level variation is an important consequence of climate change and involves many components of the climate system. In terms of global mean, interannual to decadal sea level change mainly results from thermal expansion of the oceans and water mass exchanged with other reservoirs (land water reservoirs, mountain glaciers and ice sheets). Tide gauge-based observations indicate that over the past 50 yr, the rate of global mean sea level rise was on the order of 1.8 mm/yr [*Church et al.*, 2004; *Holgate and Woodworth*, 2004]. Recent estimates of the thermal expansion contribution based on global ocean temperature data for 1950–2000 give values around 0.4 mm/yr [*Levitus et al.*, 2005; *Lombard et al.*, 2005]. Mountain glaciers melting accounts for ~0.4 mm/yr sea level rise over the last 35 yr [*Meier and Dyurgerov*, 2002]. Most recent estimates of Greenland and Antarctica melting, mostly valid for the 1990s, provide another 0.5 mm/yr contribution [e.g., *Thomas et al.*, 2004]. Summing all contributions indicates that climate-related factors explain ~1.3 mm/yr of the 1.8 mm/yr rate of sea level rise observed over the last few decades. Could the difference (~0.5 mm/yr) be explained by the land water contribution? The only study to date estimating the latter effect is that of *Milly et al.* [2003]; using the Land Dynamics -LaD- land surface model (LSM), Milly et al. 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 a significant interannual signal was reported.

[3] In this study, we extend to the past half century (1948–2000) the estimate of the contribution of terrestrial waters to sea level change, using the ORCHIDEE (Organising Carbon and Hydrology in Dynamic EcosystEms) LSM developed at the Institute Pierre Simon Laplace (Paris, France) for climate studies.

2. Short Description of the Model and the Numerical Experiment

[4] The ORCHIDEE model is used to estimate the time-varying storage of continental soil moisture and snow by solving water and energy-balance equations. A recent improvement of the model consisted of including a routing scheme, based on a simple linear cascade of reservoirs, as used for instance by *Hagemann and Dümenil* [1998]. At each time step, the runoff and drainage fluxes are temporarily stored in three reservoirs which have different residence time constants. The water is progressively routed to the oceans, following the main slopes of the topography and taking into account the tortuosity of the river channels. More detailed descriptions of the various components of ORCHIDEE can be found in work by *de Rosnay and Polcher* [1998], *Verant et al.* [2004] and *Krinner et al.* [2005].

[5] To run in a stand-alone mode, ORCHIDEE requires a high quality forcing data with sub diurnal sampling of precipitation, radiation and near-surface temperature, humidity, pressure and wind speed. Recently, *Ngo-Duc et al.* [2005], using the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kistler et al.*, 2001] and constrained by Climate Research Unit (CRU) data [*New et al.*, 2000] and the Surface Radiation Budget (SRB) data produced at the NASA Langley Research Center, have built such a near-global forcing data set, named NCC (NCEP/NCAR Corrected by CRU), for the last 53 yr (1948–2000). From the output of ORCHIDEE forced by NCC, we can study the interannual variability of surface conditions over the period of 1948–2000, as well as detect the trends. In this study, we focus on the contribution of simulated land water storage to sea level variations during the last 53 yr. Antarctica and Greenland are not taken into account in ORCHIDEE.

3. Results

3.1. Contribution of Land Water Storage to Sea Level Change Over the Last 50 Years

[6] For the past 50 yr, there is no significant trend but strong low frequency variability in the contribution of land

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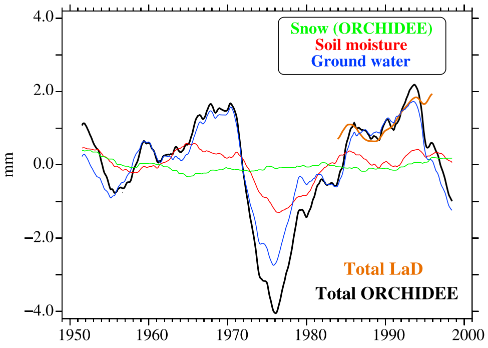

Figure 1. 5-yr moving average time series of water reservoirs changes expressed as equivalent global sea level anomalies for the past 50 yr. Red curve: soil moisture; green curve: snow pack; blue curve: groundwater; black curve: sum of the above components, which represents the land water storage variations simulated by the ORCHIDEE model. Brown curve: land water storage variations simulated by the LaD model.

water storage to sea level (Figure 1). A strong decrease in the beginning of 1970s was followed by a slow increase during the following 20 yr. The greatest variation is associated with the groundwater (the water in the river systems and in the aquifers simulated from runoff and drainage), followed by soil moisture. In the model, snow does not contribute significantly to this interannual variation. Figure 1 also shows the land water storage contribution from *Milly et al.* [2003] for the last two decades. Over their period of overlap (1981–1998), the 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 interannual/decadal variability except for 1993 when ORCHIDEE displays a downward trend, not seen in the LaD simulation.

[7] Figure 2 shows geographically averaged precipitation, evaporation and discharge to oceans of the ORCHIDEE run. Precipitation input to ORCHIDEE is provided by the NCC data set. The low frequency variability of land water storage is directly connected to precipitation variations. Under a decrease of precipitation, the land is generally dryer; hence more water is stored in the oceans. As expected, the discharge from the continents to the oceans varies in phase with the land precipitation. The simulated evaporation also shows low frequency variability, but not as strong as discharge.

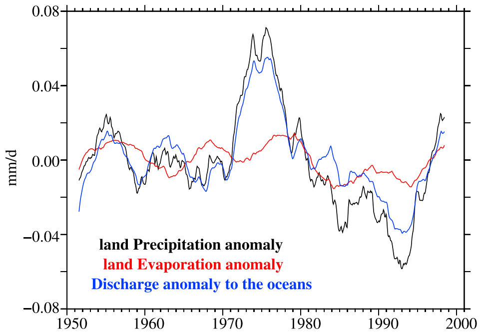

Figure 2. Anomaly time series (5-yr moving average) of land precipitation, land evaporation and discharge to the oceans for the past 50 yr.

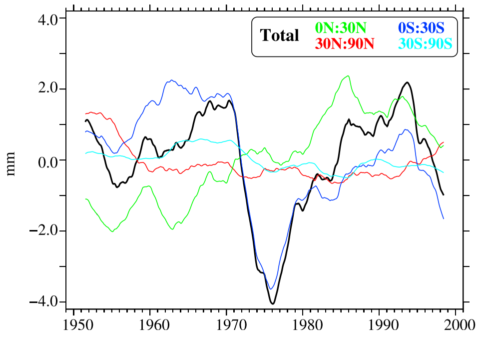

Figure 3. 5-yr moving average time series of changes in land water storage expressed as equivalent global sea level anomalies for the past 50 yr. Black curve: global mean; red curve: average from 30°N to 90°N; green curve: average from 0°N to 30°N; blue curve: average from 0°S to 30°S; cyan curve: average from 30°S to 90°S.

[8] During the period of 1975–1993, the ORCHIDEE simulation shows an increase of 0.32 mm/yr for the total land water contribution. This strong increase appears to reflect natural long-term (20–25 yr periodicities) variability rather than systematic changes in hydrological condition.

3.2. Land Water Changes in the Tropical Zone

[9] Figure 3 presents equivalent sea level variations of land water storage, averaged over different latitudinal bands. The strong global change seen during the 1970s appears totally explained by changes occurring in the southern tropics (0°–30°S). Beyond 1980, large variations occur in the northern tropics (0°–30°N). The contribution of mid and high latitudes is small for both hemispheres. Over the northern tropics, there is an increasing trend of land water contribution to sea level, which means that the northern tropics lost water to the benefit of the oceans during the last 50 yr.

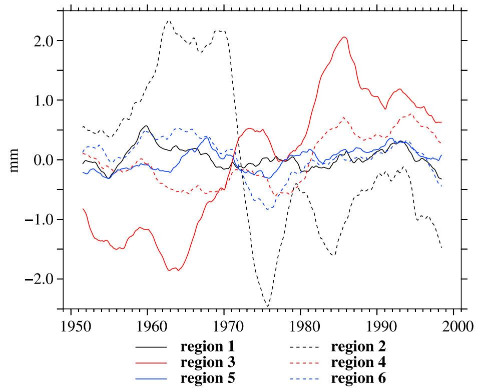

Figure 4. 5-yr moving average time series of changes in land water storage for the six studying regions, expressed as equivalent global sea level anomalies for the past 50 yr. Region 1: Central America, 0°–30°N, 125°W–25°W; region 2: South America, 0°–30°S, 125°W–25°W; region 3: north tropical Africa, 0°–30°N, 25°W–50°E; region 4: south tropical Africa: 0°–30°S, 25°W–50°E; region 5: India and southeast Asia, 0°–30°N, 50°E–125°E; and region 6: Indonesia and Australia, 0°–30°S, 50°E–125°E.

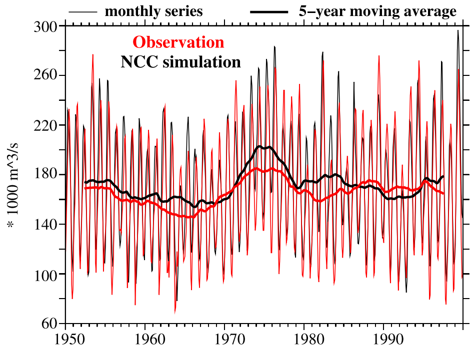

Figure 5. Discharge at the station Obidos, Amazon. Black curves: NCC simulation; red curves: observations of the HYBAM group.

[10] How can these large variations, that seem to occur preferentially over one hemisphere from the 1970s and to occur in two hemispheres during the 1980s, be understood? To investigate this, we analyzed land water storage change over six regions located in the tropics: Central America (region 1), South America (region 2), northern tropical Africa (region 3), southern tropical Africa (region 4), India and southeast Asia (region 5), Indonesia and Australia (region 6).

[11] Figure 4 shows land water storage variations over 1950–2000 for the six regions. We note that the largest variations arise from region 2 (South America) and region 3 (northern tropical Africa). In particular, the strong decrease of the early 1970s seen in Figure 3 is due to the Amazon basin. The river discharge computed by ORCHIDEE at Obidos (1.95°S, 55.51°W; the closest station on the Amazon river to its mouth) is compared with the observations of the HYBAM (Hydrogeodynamique du Bassin Amazonien) group [*Callède et al.*, 2004] (Figure 5). We found a high correlation (0.9) between model predictions and observations over the past 50 yr. In particular the model predicts well the observed discharge increase in the early 1970s, an indication of a significant land water storage increase (hence a contribution to sea level decrease).

[12] Figure 4 also shows that the positive trend of the northern tropics (Figure 3) results mainly from the northern tropical Africa contribution. During the last 50 yr, this region lost water to the benefit of the oceans. This result agrees well with observations of Lake Chad's shrinking: formerly of about 24,000 km^2 in the 1950–1960s, the area of Lake Chad has since varied between 2000 and 15,000 km^2 depending on years and seasons [*Lemoalle*, 2004].

[13] Figure 4 indicates that the contributions to sea level of regions 2 and 3 are highly anti-correlated (−0.78) over the period of 1957–1993, suggesting a possible teleconnection mechanism between the two regions. This opposition in the hydrological budget between tropical Africa and South America has been recorded for the past millenniums [*Marchant and Hooghiemstra*, 2004]. Understanding this mechanism is interesting but would go beyond the scope of this paper.

3.3. Relations Between Land Water-Based and Thermosteric Sea Level Fluctuations at Decadal/Interdecadal Time Scales

[14] In Figure 6, we have superimposed the land water storage contribution estimated in the present study and the thermosteric (i.e., due to thermal expansion) sea level curve for the past 50 yr. The thermosteric sea level was computed by *Lombard et al.* [2005] using two global ocean temperature data sets [*Ishii et al.*, 2003; *Levitus et al.*, 2005]. They cover the periods 1950–1998 and 1955–2003 respectively. The thermosteric effects inferred from the Ishii and Levitus data display similar interannual/decadal variability and thus only the one computed from the 0–500 m data of Levitus et al. is shown in Figure 6. Since there is no significant trend in the land water storage contribution (section 3.1), we have removed the trend in the thermosteric signal to make Figure 6 more readable.

[15] A clear negative correlation appears in Figure 6 between thermosteric sea level and the land water contribution, at decadal/interdecadal time scales. For the period of overlap, the correlation is −0.84.

[16] As the thermosteric sea level closely follows the variations of the ocean heat content [e.g., *Levitus et al.*, 2005], increasing thermosteric sea level corresponds to ocean warming. *Lombard et al.* [2005] showed that temperature change in the upper ocean layers mostly contributes to thermosteric sea level change. We further checked that thermosteric decadal variability mainly arises from the tropical oceans (30°S to 30°N). The anti-correlation between thermosteric sea level and land water storage fluctuations may be explained by 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 for the thermal expansion contribution to sea level change.

4. Conclusions

[17] This study has estimated the contribution of land water storage to sea level change over the past half century. We show that over the past half century the contribution of land water storage to sea level has no significant trend but displays strong decadal variability, mainly due to changes in hydrological basins of South America and northern tropical Africa. We also report a high negative correlation between the contribution of land water to sea level and thermal

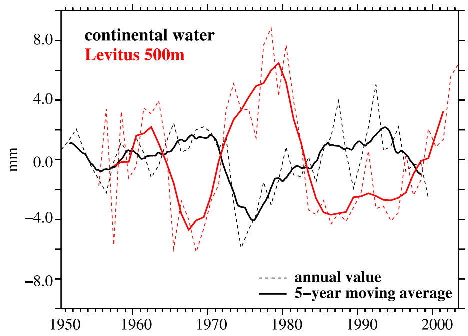

Figure 6. Time series of changes expressed as equivalent global sea level anomalies (mm) for the past 50 yr. Black curve: land water simulated by the ORCHIDEE LSM forced by the NCC forcing data; red curve: Levitus thermosteric down to 500 m.

expansion of the oceans, suggesting that change in ocean heat content has significant influence on the global hydrological cycle. This result somewhat contradicts the suggestions of *Gregory et al.* [2004] that decadal fluctuations in ocean heat content reported by recent analyses of global ocean temperature data sets are not real, but artifacts of the interpolation processes of raw hydrological data. Our result also indicates that at decadal time scales there is partial compensation between thermal expansion and land water contribution to sea level.

[18] In the absence of direct observational data at global scale, this study provides an interesting alternative of using an LSM driven by observation-based atmospheric forcing data to estimate the contribution of land water storage to sea level change over recent past decades.

[19] **Acknowledgments.** The authors wish to thank Bryan C. Weare and Alan Robock for helpful suggestions on improving the manuscript. They also thank C. Milly and an anonymous referee for helpful reviews.

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