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Detecting Groundwater Storage Change within the Great Lakes Water Basin using GRACE

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Summary

The Great Lakes Water Basin (GLB) comprises one of the most important hydrologic systems in the world. Although the change of lake levels is well-gauged, the dynamic flow and state of groundwater storage within the GLB and its interaction with the lakes are inadequately understood. In this study, the groundwater storage change within the GLB is estimated using the monthly GRACE gravity observations, as well as soil moisture models from Global Land Data Assimilation System (GLDAS) [*Rodell et al. 2004*] and water level records of the lakes for the period of 2002-2008. Results show that the Total Water mass Storage (TWS) change estimated from GRACE is comparable with the soil moisture content change in terms of both phase and amplitude. The seven-year time series of water storage changes obtained for soil moisture (GLDAS model output) and lake levels (water gauges), along with the TWS change from GRACE vary with the respective Root-Mean-Squares (RMS) of 34, 33 and 33 km^3 over the whole GLB. From these independent measures, estimates of seasonal groundwater storage changes vary from -44 to 47 km^3 with a RMS of 18 km^3 about the seven-year mean after removing a seven-year trend. These estimates quantify the groundwater recharge and discharge cycles. For the seven-year period, the storage of groundwater and lake water within the basin declined at a rate of 3.8 ±2.3 km^3/yr and 2.4 ±1.5 km^3/yr on average, respectively. Groundwater and lake water storage change are shown to respond to TWS change with phase delays of about 7 and 3 months, respectively. This study also reveals that the mass increase from glacial isostatic adjustment and TWS loss are of comparable magnitude within the GLB.

Introduction

Groundwater storage is a primary reservoir of the hydrologic cycle in the Great Lakes Water Basin (GLB). Groundwater recharge and discharge patterns are not well understood compared to other primary reservoirs such as soil moisture, surface waters, ice and snow, which are operationally gauged by *in situ* and remote sensors at various spatiotemporal resolutions for the development and management of water resources. Grannemann et al. [*2000*] suggest that more work needs to be done to define and quantify the interactions between regional groundwater flow and groundwater discharge into the Great Lakes to understand the GLB system. In 1995, groundwater supplied drinking water for about 21.8 million people on the southern side of the GLB. The total withdrawal of groundwater was 2.1 km^3/yr which included 1.3 km^3/yr for drinking water [*Solley et al. 1998*]. On the Canadian side, all groundwater withdrawal for drinking purposes comes from aquifers located within the GLB in the province of Ontario. There are 3.6 million people relaying on groundwater use with a total withdrawal of 0.2 km^3/yr. The total estimated groundwater storage is about 4000 km^3 within the GLB. With economic and societal development, the demand for groundwater continues to increase in the region. It is necessary to develop groundwater resources in a sustainable way, which requires the knowledge of groundwater recharge and discharge, fluxes for which adequate measurement techniques are not available in many instances [*Rivera 2008*].

The joint US-German Gravity Recovery And Climate Experiment (GRACE) Mission, launched on March 17, 2002, is a new type of remote sensor that can infer terrestrial Total Water mass Storage (TWS) change from its monthly gravity solutions [*Tapley et al. 2004*]. Estimates of the GRACE TWS change have a spatial resolution of better than 500 km and an accuracy of about 1 to 2 cm in Water Thickness Equivalent (WTE) [*Chen et al. 2009*]. With auxiliary measurement of surface water, soil moisture, snow and ice changes, it is possible to detect the groundwater change over a water basin covering an area larger than the GRACE spatial resolution. The fact that the GLB basin covers an area greater than the GRACE spatial resolution makes it possible for GRACE to detect the groundwater storage change within this region as long as the groundwater storage change signal is strong enough.

Method

Due to the limited coverage of the GRACE orbits in both time and space, the monthly GRACE gravity fields are strongly contaminated by stripe-like noise stretching from the Arctic to the Antarctic. The noise can be many times stronger than the Earth's seasonal and secular gravity change signal, and therefore it is necessary to smooth or remove the noise to extract the gravity change signal. In this study, a two-stage approach is developed including a de-correlation [*Swenson and Wahr 2006*] and a statistical test [*Davis et al. 2008*] (Figure 1). The two-stage approach efficiently extracts the GRACE signal while avoiding the loss of signal in association with the two methods above.

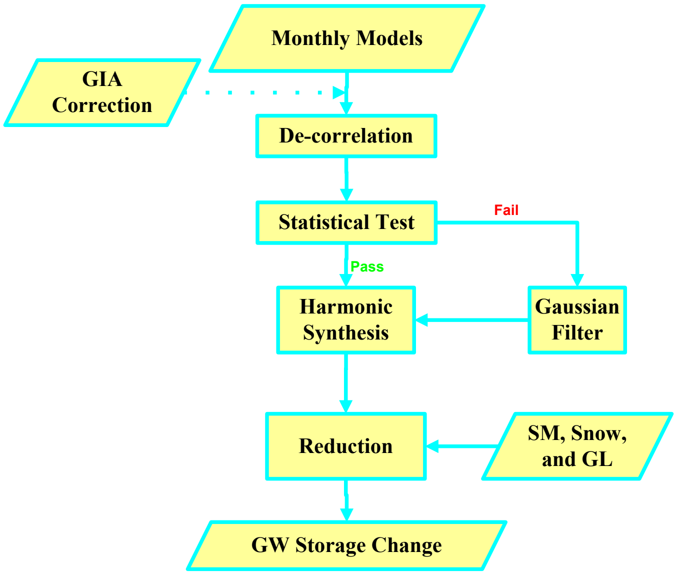

Figure 1. The processing flowchart of estimating the groundwater storage change from GRACE. (GIA = Glacial Isostatic Adjustment; GL = Great Lakes; GW = Groundwater; SM = Soil Moisture)

Preliminary Results

The monthly GRACE models have been corrected for the solid Earth and oceanic tides, selected secular variations, pole-tide effects, and a combination of atmospheric and oceanic non-tidal variation which are determined and modeled from other independent methods [*Tapley et al. 2004*]. The remaining temporal variation includes total water mass storage changes, uncorrected geophysical changes such as glacial isostatic adjustment (GIA) effect, the errors from the above mentioned corrections and GRACE observation errors. The monthly GRACE models (Release 4 by the Center for Space Research (CSR)) for the period of 2002 - 2008 have been used to estimate the groundwater change within the GLB along with the GLDAS soil moisture models, the lake water level observations, and the ICE-4G GIA model, following the approach described in Figure 1.

Figure 2 shows the map of groundwater storage change trend in WTE. This preliminary result suggests the systematic loss of groundwater storage at 3.8±2.3 km^3/yr within the GLB in contrast to 2.4±1.5 km^3/yr over lakes for the seven-year period. The groundwater loss is also comparable with the total groundwater withdrawal of 2.3 km^3/yr within the basin. It is yet to be understood how these changes are related. Further studies are also needed to refine this loss trend mainly through improving the glacial isostatic adjustment correction to the GRACE solutions, and through quantifying the uncertainty of the GLDAS soil moisture model.

Figure 3 shows annual variations of different water storage components. Among them, the soil moisture shows the strongest seasonal variation, while the groundwater shows the weakest variation. The GRACE total water storage change demonstrates the closest correlation with the soil moisture change in phase. The soil moisture change leads in phase by 4 and 8 months with respect to the lake water storage and the groundwater change, respectively. These results collectively characterize the dynamic interactions of surface water, groundwater and soil moisture components within the GLB.

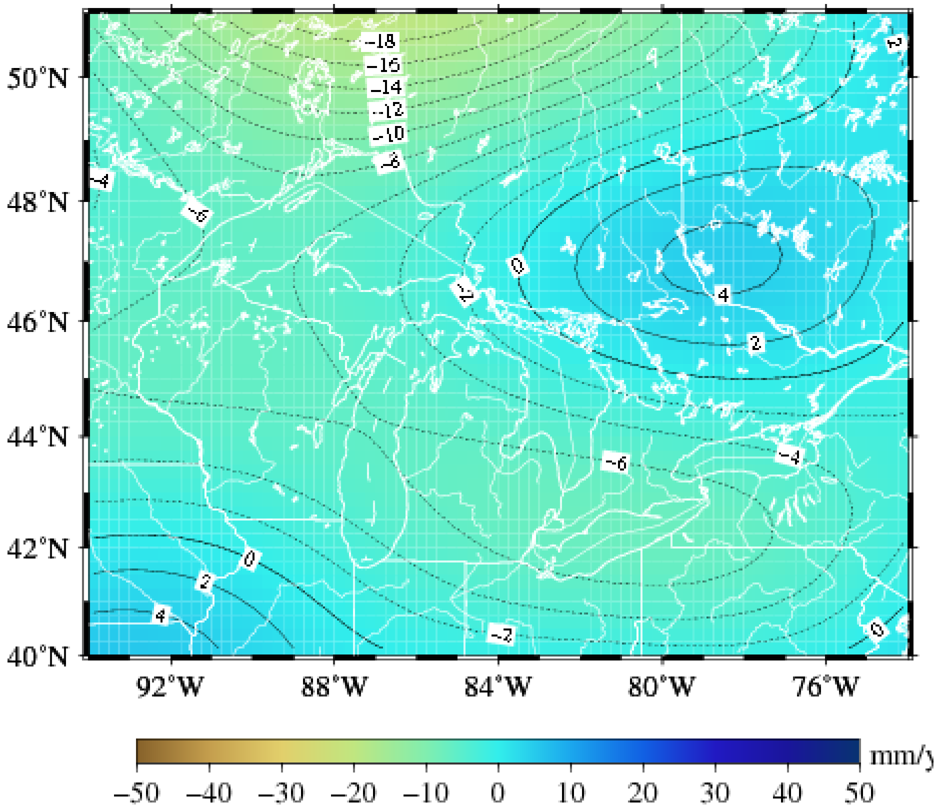

Figure 2. The trend of groundwater storage change estimated from the monthly GRACE gravity models. Unit: mm in water thickness equivalent.

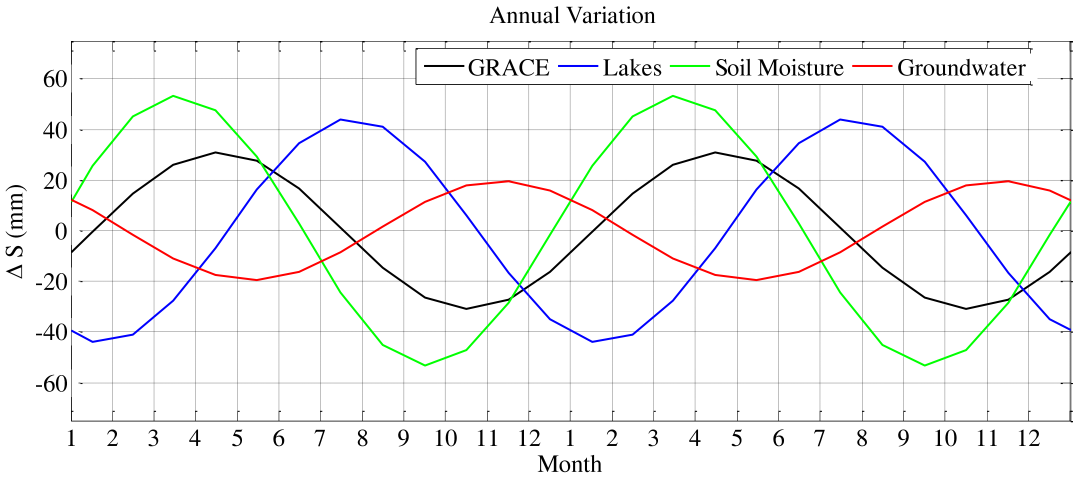

Figure 3. Annual groundwater storage change estimated from the monthly GRACE gravity models and its relation with the GRACE TWS change, as well as the lake and soil moisture water storage changes. Unit: mm in mean water thickness equivalent over the GLB.

Conclusions

The seven-year GRACE observations have been used to detect the groundwater storage change over land within the Great Lakes Basin along with water level gauge observations over the lakes and the GLDAS soil moisture models. The results show that seasonal groundwater storage changes vary from -44 to 47 km^3 with a RMS of 18 km^3 about the seven-year mean reflecting annual discharge and recharge cycles for the period of study. The seasonal changes account for about 1 percent of the total groundwater storage within the GLB. For this period, the storage of groundwater and lake water declined at a rate of 3.8±2.3 km^3/yr and 2.4±1.5 km^3/yr on average, respectively. Further studies are needed to understand if the groundwater loss is related to the estimated total groundwater withdrawal of 2.3 km^3/yr and increasing groundwater discharge to the Great lakes to respond the lake water loss. Seasonal groundwater and lake water storage changes are shown to respond to TWS change with phase delays of about 7 and 3 months. This study also reveals that the mass increase from glacial isostatic adjustment and TWS loss are of comparable magnitude within the GLB.

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