Integration of GRACE (Gravity Recovery and Climate Experiment) data with traditional data sets for a better understanding of the time-dependent water partitioning in African watersheds

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ABSTRACT

Monthly (71 months) Gravity Recovery and Climate Experiment (GRACE) gravity field solutions acquired over North and Central Africa (August 2002–July 2008) were destriped, smoothed (250 km; Gaussian), and converted to equivalent water thickness. These data were analyzed in a geographic information system environment together with relevant data sets (e.g., topography, geology, remote sensing) to assess the utility of GRACE for monitoring elements of hydrologic systems on local scales. The following were observed over the Niger, Congo, and Nile Basins: (1) large persistent anomalies (standard deviation, SD > 10 cm) on SD images over periods of 2–7 yr; (2) anomalous areas originate at mountainous source areas that receive high precipitation, extend downslope toward mountain foothills, and often continue along main channels, wetlands, or lakes that drain these areas; (3) time-series analyses over anomalous areas showed that seasonal mass variation lags behind seasonal precipitation; and (4) seasonal mass variations showed progressive shift in phase and decrease in amplitude with distance from the mountainous source areas. Results indicate that (1) the observed temporal mass variations are largely controlled by elements of the hydrologic cycle (e.g., runoff, infiltration, groundwater flow) and have not been obscured by noise, as previously thought; and (2) it is possible to use GRACE to investigate the temporal local responses of a much larger suite of hydrologic systems (watersheds, lakes, rivers, and marshes) and domains (source areas and lowlands) within watersheds and subbasins worldwide.

INTRODUCTION

The Gravity Recovery and Climate Experiment (GRACE) satellite mission was launched in March 2002 to map the temporal variations in the Earth’s global gravity field on a monthly basis (Tapley et al., 2004). The variability in these gravity field solutions represents geophysical responses associated with redistribution of mass at or near the Earth’s surface, where mass variations are likely to occur on the time scales examined by GRACE measurements. Generally, the largest time-variable gravity signals observable in GRACE data are expected to come from changes in the distribution of water and snow stored on land (Wahr et al., 1998). The majority of studies utilizing GRACE data for hydrological research and applications (e.g., Chen et al., 2005; Rodell et al., 2004) target large watersheds (areas of 450 × 10⁶ to 6 × 10⁶ km²), because the accuracy of the recovered mass variations increases with increasing size of the monitored basin (Wahr et al., 2006). Gaussian filters ranging from 600 to 1200 km in radius were applied in studies on the central United States High Plains Aquifer, the Amazon Basin, the upper Zambezi Basin, and the Mississippi River Basin (Chen et al., 2005; Rodell and Famiglietti, 2002; Rodell et al., 2004; Syed et al., 2005; Winsemius et al., 2006).

We show that temporal mass variations from the GRACE data acquired over North and Central Africa and as far as 10°S of the equator, when smoothed using a 250-km-radius Gaussian function, are largely controlled by elements of the hydrologic cycle, and have not been obscured by noise as previously thought.

DATA PROCESSING

We analyzed 71 gravity field solutions (RL04 unconstrained solutions) that span the period August 2002 through July 2008 from the GRACE database provided by the University of Texas Center of Space Research. The gravity field solutions were processed as follows. (1) The temporal mean was removed. (2) Correlated errors were reduced by applying destriping methods developed by Swenson and Wahr (2006). (3) Spherical harmonic coefficients were converted to grids (0.5° × 0.5°) of equivalent water thickness using a Gaussian smoothing function with a radius of 250 km. (4) Standard deviation (SD) images were generated from the equivalent water thickness grids over periods of 2, 3, 4, 5, 6, and 7 yr. (5) Amplitude and phase of annual cycle images were generated from the equivalent water thickness grids.

All GRACE-derived mass fields were interpreted as reflecting changes in water storage, given (1) the slow rates of the mass variations in the underlying solid Earth, (2) absence of large earthquakes and glacial isostatic adjustment in the region, and (3) the small to negligible contributions related to mass fluctuations from adjacent ocean (Wahr et al., 1998) and the corrections applied to remove time-variable oceanic gravity signal from raw GRACE measurements (Tapley et al., 2004).

The spatial distribution of GRACE SD data was compared to other relevant geologic, topographic, and hydrologic data in a geographic information system (GIS) environment and made available for researchers via a web-based GIS (www.esrs.wmich.edu/webmap) in order to identify areas exhibiting large temporal mass variations and investigate the forcing parameters giving rise to these variations. The GIS included the following data: (1) GRACE monthly images, SD images, and amplitude and phase of annual cycle images; (2) monthly, annual,
DISCUSSION AND CONCLUSION

Examination of the SD images that were generated from monthly GRACE solutions over periods of 2, 3, 4, 5, and 6 yr, as well as over the entire examined period (Fig. 1), showed persistent patterns. The persistent spatial characteristics of the SD anomalies contrast with those of the surface mass anomalies derived from the individual monthly GRACE solutions: the latter showed pronounced anomalies that vary in location and magnitude and are largely concentrated in sub-Saharan and tropical Africa. One interpretation for the observed persistent nature of the anomalous areas on the SD images is that they represent areas that are largely controlled by inherent mass variations (signal) that are modulated, but not obscured, by noise.

Figures 2A and 2B show a three-dimensional representation of SD images of both GRACE and TRMM data over the examined time period. As is the case with GRACE data, the temporal mean precipitation was removed from monthly precipitation for each pixel element. Using arbitrary threshold SD values, we classify the mass anomalies displayed in Figures 1 and 2A into three major groups: (1) areas of high mass variations (SD > 10 cm); (2) areas with intermediate variations (10 cm > SD > 6 cm); and (3) areas with low to no variations (SD < 6 cm). Areas displaying intermediate to high mass variations on SD images are located in sub-Saharan Africa, whereas Saharan Africa displays negligible mass variations. The Sahel region, which separates Saharan from sub-Saharan Africa, shows intermediate to small mass variation. Similar spatial precipitation patterns were observed over Saharan and sub-Saharan Africa and the Sahel region; this suggests a causal effect (Fig. 2B). One should not expect a one-to-one correspondence between mass variation and precipitation patterns, given that precipitation could readily be redistributed as runoff, recharge, evaporation, and transpiration, all of which could affect the spatial and temporal distribution of the precipitated water and hence the location and magnitude of the SD anomalies.

All of the pronounced anomalous areas (SD > 10 cm) were found within relatively large regions and total (2002–2008) precipitation images, SD images, and amplitude and phase cycle images, all extracted from Tropical Rainfall Measuring Mission (TRMM) data; (3) digital elevation model (DEM) extracted from Shuttle Radar Topography Mission (SRTM) data products; (4) slope data extracted from DEM; (5) geologic maps for Africa (Choubert and Faure-Muret, 1987); (6) false-color Landsat Thematic Mapper (TM) data; (7) stream networks and watershed boundaries extracted from the SRTM data set; and (8) distribution of surface water bodies extracted from SRTM and Landsat TM data, and geologic maps. Findings based on the examination of these spatial and temporal data sets are given in the following.

Figure 1. Standard deviation (SD) image derived from equivalent water thickness grids (0.5° × 0.5°) from Gravity Recovery and Climate Experiment (GRACE) monthly solutions (71 months) acquired for North and Central Africa (August 2002–September 2008). Also shown are locations of major rivers (blue lines), highlands (dashed black lines), wetlands (dashed brown lines), basins (purple lines), and lakes (solid triangles). DRC—Democratic Republic of the Congo; CAR—Central African Republic.
to medium-sized basins (e.g., Congo River Basin, area 3,712,739 km²; Niger Basin, area 2,144,785 km²; Nile Basin, area 3,086,409 km²). Next, we show that these anomalous areas originate in mountainous source areas that receive high precipitation; they extend downslope toward the mountain foothills and often continue along the main channels, wetlands, or lakes draining these areas (Fig. 1).

The Congo River Basin receives the highest amount of precipitation (average annual from TRMM [AATRMM] 2000 mm/yr) of all the major watersheds in Africa and has the strongest SD anomalies. The GRACE anomalies within the Congo River Basin originate from mountainous areas that have high precipitation, namely the Albertine Rift range (anomaly location [AL] C1), the Ironstone Plateau (AL C2), the Adamaoua Plateau (AL C3), the Lunda Plateau (AL C4), and Muchinga Mountains (AL C5). To a large extent, the anomalies then follow the main tributaries that drain these highlands and ultimately extend into the Congo River (length 4700 km) through the Democratic Republic of the Congo.

Precipitation over the Albertine Rift range (AATRMM 2000 mm/yr), Muchinga Mountains (AATRMM 1010 mm/yr), and the Lunda Plateau (AATRMM 350 mm/yr) is channeled through the Lukuga (length 320 km, AL C6), Lualaba (length 1800 km, AL C7), Lomami (length 1500 km, AL C8), Kwango (length 1100 km, AL C9), Kwilu (length 600 km, AL C10), and Kasai (length 1800 km, AL C11) Rivers and the tributaries of the Kasai River, the Lulua (length 420 km, AL C12) and Sankuru (length 1230 km, AL C13) Rivers. The Ironstone Plateau [average height (AH) 600 m above mean sea level, amsl] precipitation (AATRMM 1500 mm/yr) feeds the Ubangi River (length 1100 km, AL C14) and its tributaries, whereas the Adamawa Plateau (AH 1000 m amsl) precipitation (AATRMM 1500 mm/yr) is channeled through the Sangha affluent (length 850 km, AL C15).

The GRACE anomalies within the Niger Basin originate from the Fouta Djallon range (AH 1100 m amsl), which receives the highest amount of precipitation (AATRMM > 2000 mm/yr) in Guinea, and the Nimba Range (highest point 1752 m amsl) along the borders of Guinea and the Côte d’Ivoire (AL G1), which receives AATRMM of 3000 mm/yr. The anomalies then extend northeast along the Niger River (AL G2). The Niger River (length 4200 km) anomaly decreases with distance from the source area, but it is emphasized again (AL G3) at its junction with the Sokoto River, which channels precipitation from the Jos Plateau (AH 1280 m amsl, AATRMM 1200 mm/yr). Other anomalous areas originate at the highlands of Cameroon (Adamawa Plateau), then follow the Benue River (AL G4), the major tributary of the Niger River (length 1400 km), toward its junction with the Niger River, and extend over the massive delta where the two rivers discharge into the Atlantic Ocean (AL G5) in the Gulf of Guinea.

The GRACE anomalies within the Nile Basin originate from mountainous areas along the western margins of the Ethiopian highlands (ALs N1 and N2), the largest continuous area of its altitude (AH > 1500 m amsl) in Africa and the northern parts of the Ironstone Plateau (AL N3). Precipitation over the northwest part of the Ethiopian highlands (AATRMM 1400 mm/yr) drains into Lake Tana (elevation 1840 m, area 3156 km²), where the Blue Nile (length 1450 km) originates. The SD anomalies follow the Blue Nile from the highlands to its intersection with the White Nile (AL N5), where the anomaly is emphasized.

Anomalous areas on the SD images are also observed over the subbasins that ultimately feed the White Nile; these anomalous areas start in the source highland areas, pass by lakes and wetlands, and follow the main tributaries up to the point where the White Nile emerges. Precipitation over the northern parts of the Albertine Rift and the Kenyan highlands (AATRMM 2000 mm/yr) are channeled (e.g., by the Kagera River) to Lake Victoria (elevation 1135 m amsl), Africa’s largest lake (area 68,800 km²) (AL N4). The Victoria Nile exits Lake Victoria to Lake Kyoga (area 1720 km²) and Lake Albert (area 5300 km²), and then continues its journey towards the Sudan as the Albert Nile, where its name changes to Bahr al Jabal (length 716 km) and it joins with Bahr al Jazal and Sobat (length 320 km) to form the White Nile.

There is a general correlation between precipitation patterns and SD anomaly patterns (Figs. 2A and 2B) and the spatial correlation of anomalous areas on the SD image with (1) mountainous source areas receiving high precipitation, and (2) elements of drainage systems, including rivers, lakes, and wetlands that channel and/or collect precipitation from the source areas. This supports the suggestion that the observed GRACE mass variations are related to elements of the hydrological cycle (e.g., infiltration, recharge, and/or surface runoff, and/or groundwater flow) observed at the subbasin scales examined here.

This suggestion is supported by the seasonal patterns observed in the time-series analysis for the GRACE monthly gravity solutions. Figure 3 displays examples of this mass variability observed in monthly data (from January 2003 to December 2007) acquired over source areas (ALs C3 and C5, Congo River Basin; G1, Niger Basin; N1, Nile Basin). Comparisons to precipitation time series for the same areas indicate that the GRACE solutions and precipitation data display similar seasonal patterns, but GRACE seasonal variations lag a month or two behind precipitation. In the Niger Basin (point G1; Fig. 3A), we find that the highest rainfall occurs between July and August and the largest increase in mass is between September and October. Similarly, maximum rainfall in the Nile Basin (point N1; Fig. 3B) is between July and August, a month or two ahead of GRACE SD peaks (September to October). In the northern part of the Congo River Basin (point C3; Fig. 3C), GRACE SD peaks lag a month or two behind rainfall (August to September); they lag a month or two behind rainfall (December, January, and February) in the southern parts of the Congo River Basin (point C5; Fig. 3D) as well. Findings are supported by reported observations for the timing of peak precipitation and flow in these three basins (e.g., Chishugi and Alemaw, 2009).

One explanation is that with the onset of the precipitation period, which occurs mostly over the mountainous areas, a good fraction of this water is captured through initial losses, increasing soil moisture and creating local ponds and sinks, thus increasing the accumulated water and mass. With continued precipitation and mass accumulation, GRACE response will continue to rise and perhaps peak at a point where...
the soil moisture content approaches saturation. When precipitation starts to decline, mass accumulation gradually diminishes to the point at which water received in the soil profile from precipitation is less than that lost to evapotranspiration and to outflows (runoff, overland flow, interflow, and groundwater flow). This marks a halt in additional increases in water thicknesses and the onset of the effects of mass deficiency. As the rainy season comes to an end, precipitation tapers off, and factors such as evapotranspiration and runoff progressively decrease accumulated water, reducing the GRACE response until it bottoms out.

If this conceptual model is true, one would expect the amplitude of the annual cycle from GRACE data to decrease with distance from the source areas because (1) the source areas by nature receive the highest amounts of precipitation, and (2) only a portion of this precipitation moves toward the lowlands downstream as runoff, overland flow, interflow, and groundwater flow in shallow aquifers. One would also expect a progressive shift in phase of the annual cycle from GRACE data with distance from the source area because of the time it takes for runoff, overland flow, interflow, and/or groundwater flow in shallow aquifers to move the water from the highlands to the lowlands. The shift here refers to the shift of the peak and/or trough observed in a single annual cycle in the monthly GRACE solutions.

Inspection of the amplitude of the annual cycle image that was generated by fitting a sinusoidal model to a period of 12 months to the data points for years 2003–2007 (Fig. 2C) shows that the amplitude over mountainous areas that receive high precipitation (e.g., areas labeled N, C, C′, G; Fig. 2C) is high and declines downstream with distance from the highlands (e.g., traverses N-N′, C-C′, C′-C″; Fig. 2C). The phase of the annual cycle image of monthly TRMM precipitation data and for monthly GRACE data for the same year are displayed in Figures 2D and 2E, respectively; on these images, peak precipitation or mass are assigned values ranging from 1 (January) to 12 (December). Over the mountainous source areas in the Nile, Congo (northern part), and Niger Basins, areas labeled N, C, and G in Figure 2D, the peak precipitation occurs largely in the months of July, August, and September, respectively, and is monsoonal in origin (e.g., Chishugi and Alemaw, 2009). Peak monthly GRACE values progressively shift to October, November, and December, respectively, with distance from the mountainous areas. Progressive shift in phase with distance from the mountainous source areas is observed; the steeper the source areas, the smaller the distance over which mass variations are observed (e.g., traverses N-N′, C-C′, C′-C″; Fig. 2E). That is to be expected, because the steeper the gradient, the faster the water will move out of it.

Results show that high mass variations observed over anomalous areas on the SD images are largely controlled by elements of the hydrologic cycle such as runoff, infiltration, and groundwater flow, and that these mass variations are probably modulated, but not obscured by noise as previously thought. Nevertheless, the presence of systematic artifacts over some of the areas showing low mass variations cannot be ruled out. Our findings suggest that it is possible to use GRACE to study temporal local responses of a much larger suite of smaller hydrologic systems and regions within watersheds and subbasins on the African continent and elsewhere worldwide.

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