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Water storage changes and climate variability within the Nile Basin between 2002 and 2011

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ABSTRACT

Understanding water storage changes within the Nile's main sub-basins and the related impacts of climate variability is an essential step in managing its water resources. The Gravity Recovery And Climate Experiment (GRACE) satellite mission provides a unique opportunity to monitor changes in total water storage (TWS) of large river basins such as the Nile. Use of GRACE-TWS changes for monitoring the Nile is, however, difficult since stronger TWS signals over the Lake Victoria Basin (LVB) and the Red Sea obscure those from smaller sub-basins making their analysis difficult to undertake. To mitigate this problem, this study employed Independent Component Analysis (ICA) to extract statistically independent TWS patterns over the sub-basins from GRACE and the Global Land Data Assimilation System (GLDAS) model. Monthly precipitation from the Tropical Rainfall Measuring Mission (TRMM) over the entire Nile Basin are also analysed by ICA. Such extraction enables an in-depth analysis of water storage changes within each sub-basin and provides a tool for assessing the influence of anthropogenic as well as climate variability caused by large scale ocean–atmosphere interactions such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Our results indicate that LVB experienced effects of both anthropogenic and climate variability (i.e., a correlation of 0.56 between TWS changes and IOD at 95% confidence level) during the study period 2002–2011, with a sharp drop in rainfall between November and December 2010, the lowest during the entire study period, and coinciding with the drought that affected the Greater Horn of Africa. Ethiopian Highlands (EH) generally exhibited a declining trend in the annual rainfall over the study period, which worsened during 2007–2010, possibly contributing to the 2011 drought over GHA. A correlation of 0.56 was found between ENSO and TWS changes over EH indicating ENSO's dominant influence. TWS changes over Bar-el-Ghazal experienced mixed increase–decrease, with ENSO being the dominant climate variability in the region during the study period. A remarkable signal is noticed over the Lake Nasser region indicating the possibility of the region losing water not only through evaporation, but also possibly through over extraction from wells in the Western Plateau (Nubian aquifer).

1. Introduction

The Nile River Basin is one of the largest basins in the world, with an area of about 3,400,000 km^2 (almost one-tenth of Africa). It traverses about 6,500 km from the White Nile in the south to the Mediterranean Sea in the north as it winds its way across the boundaries of eleven countries supporting livelihoods of over 300 million people [2]. Because of this huge size of the Nile Basin, climate variability and change that is manifested locally or regionally may have regional and even international consequences through its effects on Nile river flows [19].

The Nile's water resources have come under threat from both anthropogenic and natural factors (see, e.g., [33]). Indeed, that hydrological regimes respond to climate change and anthropogenic influences have been reported, e.g., in [13,38,22]. For the Nile River Basin, anthropogenic influences are attributed to increased human population that has put pressure on domestic water needs and hydroelectric power supply, all coupled with the need to sustain economic growth (e.g., [2,3,6,7]). Furthermore, not only are the

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demands on water increasing, but also the available water supplies appear to be decreasing, with environmental degradation of the upper Blue Nile catchment having increased throughout the 1980s [76]. For example, due to the large and increased population pressure, insufficient agricultural production, a low number of developed energy sources, and drought episodes; Ethiopia, which contributes about 85% of the Nile's annual flow [66], but has almost 94% of its population depending on wood fuel, is planning major hydropower and irrigation development [12,15,72,73]. In addition to irrigation and hydroelectric power, land degradation and changes in land cover in Ethiopia where forest lands are being converted to agricultural land are having impact on the Nile flow (see, e.g., [52,63]). Such measures are likely to impact on the downstream countries of Egypt and Sudan whose populations have been increasing, thus posing a challenge to water allocation (see [2,3,7,76]).

Natural factors have been the subject of numerous studies as shown in the works of Beyene et al. [13], Conway [19] and Yates [77, and the references therein] who investigated the influence of the changing climate on the Nile waters; Ghoubachi [32] and Sefelnasr [62] who considered groundwater movement. For the Nile river discharge, for example, the influence of climate variability and change has been shown e.g., by Eltahir [24] and Amarasekera et al. [1] to account for 25% of natural variability in annual discharge. Knowledge of climate variability is essential not only for predicting its floods and droughts [24,39], but also for understanding of global atmospheric dynamics since streamflow is an index of precipitation integrated over large areas [1].

To support the management of the Nile Basin's water resources (e.g., *supply*, *demand* and *sustainable use*; Hanson et al. [34]), it is essential to understand the changes in its stored water (surface, groundwater, and soil moisture) and their relation to climate variability such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Due to its large spatial extent, however, changes in Nile Basin's stored water cannot be monitored using traditional methods (e.g., piezometric-based). This calls for satellite based methods of observation. One such satellite is the Gravity Recovery And Climate Experiment (GRACE) whose use offers a unique chance to monitor changes in the total water storage (TWS, i.e., an integral of surface, groundwater, and soil moisture storage) within the Nile Basin (see, e.g., [2,3,6,10,16,45,63,69]).

The main challenges in using GRACE-TWS changes over the Nile Basin is that on the one hand, the derived hydrological signals are dominated by stronger signals, e.g., those around the lakes such as Lakes Victoria and Tana (see, e.g., [3]), as well as regions close to the Red Sea and the Mediterranean Sea [9]. Computing basin average water variations, therefore, is normally influenced by dominant signals such as that of Lake Victoria Basin (LVB), while the relatively weaker signals from the other regions are masked making analysis of changes in TWS over such sub-basins difficult. On the other hand, Rodell and Famiglietti [54] pointed to the limitation of GRACE products to study basins of less than 200,000 km^2. Since some of the Nile's sub-basins (e.g., Lake Nasser region) have areas less than 200,000 km^2, thus, computing TWS changes of them is limited by the spatial resolution of GRACE (e.g., 400,000 km^2 in [67,70]). Previous analysis of the Nile Basin based on the GRACE satellite data have thus been unable to separate the signals into their respective sub-basins for the purpose of providing an in-depth analysis of spatial variations (see, e.g., [3]).

To overcome these challenges, in the present study; (i) we apply a higher order statistical tool of Independent Component Analysis (ICA) (Spatial ICA in [29,30]) over the Nile Basin (between 10°S–35°N and 25°E–45°E) to separate GRACE-TWS changes between 2002 and 2011 into their spatially independent sources (i.e., sub-basins). This is then followed, in (ii), by an evaluation of the impacts of global climate change on the TWS within these sub-basins using global climate forcing by IOD and ENSO.

The remainder of the study is organized as follows; in the next section, the Nile Basin is briefly described. The methodology (data used in the study and the analysis approaches) are outlined in Section 3, and the results discussed in Section 4. Section 5 concludes the major findings.

2. The Nile Basin

The Nile Basin (Fig. 1) has two major tributaries, the White Nile and the Blue Nile, the latter being the main source of its water. The White Nile originates from the Great Lakes region of Eastern Africa, and flows northwards through Uganda and South Sudan. The Blue Nile on the other hand starts from Lake Tana in the Ethiopian Highlands (EH), flowing into Sudan from the southeast and meets the White Nile at Khartoum in Sudan. From there, the Nile passes through Egypt, which is mostly dry (i.e., 92%) and Sudan, and finally discharges into the Mediterranean Sea (see, e.g., [56]).

The four main areas of interest to our study, whose changes in TWS could be remotely sensed using GRACE satellite data due to their larger spatial coverage (i.e., over 200,000 km^2) are (see Fig. 1): (i) Lake Victoria Basin (LVB), which is the headwaters of the White Nile; (ii) the Bahr-el-Ghazal region (BEG), the main western tributary of the Nile, and the largest sub-basin. Its supply to the Sudd wetlands is however reported by Mohamed et al. [46] to be negligible. Nonetheless, it is included in this study to assess the impacts of climate variability on its TWS changes. The Sudd wetlands (marshes) is the region between Mongalla and Malakal, which consists of marshes and lagoons, and is believed to be where most of the White Nile's water is lost due to evaporation [77]; (iii) the Ethiopian Highlands (EH), and the headwaters of the Blue Nile; and (iv) the Egyptian desert region consisting of Lake Nasser, where significant amounts of water are lost due to evaporation (see details of regions in [20]). The characteristics of these regions are summarized in (Table 1).

3. Data and methodology

3.1. Data

The data used in this study consisted of remotely sensed GRACE-TWS changes from 2002 to 2011, Tropical Rainfall Measuring Mission (TRMM)-derived precipitation, and water storage data from Global Land Data Assimilation System (GLDAS) hydrological model over the same period.

3.1.1. Gravity Recovery And Climate Experiment (GRACE)

GRACE, a joint US-German satellite project launched in March 2002, detects spatio-temporal variations of the Earth's gravity field [70]. There are a number of institutions delivering GRACE products, each applying their own processing methodologies and, often, different background models. In this work, we examined gravity field time series provided by the German GeoForschungsZentrum (GFZ), Potsdam [25]. GFZ's release (RLO4) gravity field solutions are provided at monthly resolutions and consist of a set of fully normalized spherical harmonic coefficients of the geopotential, up to degree and order 120. These coefficients are contaminated by correlated errors, manifesting as stripes in the spatial domain. These striping and high-frequency effects potentially mask hydrological signals, making their detection extremely difficult (e.g., [5,42]). In this regard, the GFZ solutions were smoothed using the DDK2 de-correlation filter [43]. Filtered solutions can also be downloaded from the official website of the International Center for Global Gravity Field Models.[1] We chose RLO4 version and the DDK2 filter to be consistent with previous

[1] (http://icgem.gfz-potsdam.de/ICGEM/TimeSeries.html).