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Characterization of Ethiopian mega hydrogeological regimes using GRACE, TRMM and GLDAS Datasets

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Abstract

Understanding the spatio-temporal characteristics of water storage changes is crucial for Ethiopia, a country that is facing a range of challenges in water management caused by anthropogenic impacts as well as climate variability. In addition to this, the scarcity of in-situ measurements of soil moisture and groundwater, combined with intrinsic “scale limitations” of traditional methods used in hydrological characterization are further limiting the ability to assess water resource distribution in the region. The primary objective of this study is therefore to apply remotely sensed and model data over Ethiopia in order to (i) test the performance of models and remotely sensed data in modeling water resources distribution in un-gauged arid regions of Ethiopia, (ii) analyze the inter-annual and seasonal variability as well as changes in total water storage (TWS) over Ethiopia, (iii) understand the relationship between TWS changes, rainfall, and soil moisture anomalies over the study region, and (iv) identify the relationship between the characteristics of aquifers and TWS changes. The data used in this study includes; monthly gravity field data from the Grav-

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ity Recovery And Climate Experiment (GRACE) mission, rainfall data from the Tropical Rainfall Measuring Mission (TRMM), and soil moisture from the Global Land Data Assimilation System (GLDAS) model. Our investigation covers a period of 8 years from 2003 to 2011. The results of the study show that the western part and the north-eastern lowlands of Ethiopia experienced decrease in TWS water between 2003–2011, whereas all the other regions gained water during the study period. The impact of rainfall seasonality was also seen in the TWS changes. Applying the statistical method of Principal Component Analysis (PCA) on TWS, soil moisture and rainfall variations showed the dominant annual water variability in the western, north-western, northern, and central regions, and the dominant seasonal variability in the western, north-western, and the eastern regions. A correlation analysis between TWS and rainfall indicate a minimum time lag of zero to a maximum of six months, whereas no lag is noticeable between soil moisture anomalies and TWS changes. The delay response and correlation coefficient between rainfall and TWS appears to be related to recharge mechanisms, revealing that most regions of Ethiopia receive indirect recharge. Our results also show that the TWS changes are higher in the western region and lower in the north-eastern region, and that the elevation influences soil moisture as well as TWS.

Keywords: TWS changes, Ethiopia, GRACE, TRMM, GLDAS, Hydrology, Climate

1. Introduction

Ethiopia’s hydrology plays a significant international role, being the headwaters of the Blue Nile basin, where it contributes about 86% of the total annual flow of the Nile (Melesse, 2011; Sutcliffe & Parks, 1999) and also approximately 90% of inflow into Lake Turkana (Ferguson & Harbott, 1982), a lake situated in the arid area of northern Kenya. In recent decades, however, extreme hydrological variability, seasonality, and anthropogenic factors are posing challenges to the region’s water resource management. For example, due to the large and in-

9 creasing population pressure, insufficient agricultural production, a low number
10 of developed energy sources, and drought episodes, Ethiopia, which has almost
11 94% of its population depending on wood fuel, is planning major hydropower
12 and irrigation development schemes(Tesfagiorgis et al., 2011; Berhane et al.,
13 2013). In addition to irrigation and hydroelectric dams, land degradation and
14 changes in land cover in Ethiopia where forests are being converted to agri-
15 cultural land are having impact on the Nile flow (see, e.g., Senay et al., 2009;
16 Rientjes et al., 2011).

17 Characterizing water-storage in all its forms (surface, soil moisture, and
18 groundwater) and their responses to the incoming (precipitation) and outgo-
19 ing (evaporation and discharge) water masses, therefore, is of great importance
20 in terms of understanding extreme changes in stored water triggered by nat-
21 ural and anthropogenic factors. This is of interest especially in areas where
22 the seasonality of rainfall is strong and the welfare of the society relies on the
23 availability of water, such as in Ethiopia.

24 To quantify the stored water resource of a region, soil moisture and ground-
25 water have been documented to play a significant role (e.g., Rodell et al., 2007;
26 Rodell & Famiglietti, 2001; Swenson et al., 2008). For developing countries such
27 as Ethiopia, however, in-situ networks of soil moisture and groundwater mea-
28 surements are sparse. Therefore, these components are among the most difficult
29 water budget parameters to obtain. To circumvent this shortfall, characterizing
30 the hydrogeological regimes has been undertaken by considering their hydroge-
31 ological environments (see, e.g., Ayenew et al., 2008; Furi et al., 2012; Kebede
32 et al., 2005, 2008; Yitbarek et al., 2012). Most of the previous studies have
33 concentrated on the climatic characteristics (e.g., Conway & Schipper, 2011;
34 Seleshi & Camberlin, 2006; Seleshi & Zanke, 2004; Omondi et al., 2012, 2013,
35 2014; Shang et al., 2011; Taye & Willems, 2012) and the use of environmental
36 isotopes and hydrochemicals (e.g., Berhane et al., 2013) to trace the water avail-
37 ability in Ethiopia. For example, Berhane et al. (2013) found the environmental
38 isotopes and hydrochemicals approach to be the most effective tool for differ-
39 entiating various forms of geochemical reaction, and to infer the environmental

40 factors affecting groundwater quality and its flow in the region.

41 Besides concentrating on climatic characteristics, most of the studies above
42 are also restricted to small scale hydrological characterizations, which do not
43 reflect the large-scale water storage variability over Ethiopia. Moreover, isotopes
44 and hydrochemical-based methods are costly, require skilled experts, and are
45 often difficult to apply over large areas, which are not easy to venture into,
46 particularly in developing countries such as Ethiopia. Furthermore, most of the
47 hydrological studies over Ethiopia focused only on regional characterizations.
48 Generalizing such local outputs to the whole of Ethiopia is extremely difficult
49 due to its vast range of climatic and topographic conditions.

50 Total water-storage (TWS), which is defined as the sum of all forms of
51 water stored above and underneath the Earth's surface, is a key component
52 of the terrestrial and global hydrological cycles that exerts important control
53 over water, energy and biogeochemical fluxes, and thus plays a major role in
54 the Earth's climate system (Rodell et al., 2004; Syed et al., 2008; Tapley et al.,
55 2004). The Gravity Recovery And Climate Experiment (GRACE) mission offers
56 the possibility of remotely sensing global and regional TWS changes. Launched
57 in 2002 as a joint project of the US and Germany, GRACE products have
58 contributed enormously to the study of changes in total water storage.

59 With the help of complementary data sets, GRACE-derived products offer
60 the possibility of monitoring groundwater depletion in data poor regions of the
61 world (Famiglietti & Rodell, 2013; Forootan et al., 2014; Rodell et al., 2007). To
62 date, however, except for studies that have been done at continental or global
63 scales (Reager & Famiglietti, 2009; Schmidt et al., 2008) and those in connection
64 with the Nile Basin (Bonsor et al., 2010; Melesse et al., 2010; Awange et al., 2008;
65 Awange, 2012; Awange et al., 2013a; Awange & Kyalo Kiema, 2013; Awange
66 et al., 2013b, 2014) GRACE satellite products have not been applied specifically
67 to the whole Ethiopian basins at a local level. Within Ethiopia, for example, the
68 application of GRACE products are reported e.g., in Bonsor et al. (2010) and
69 Melesse et al. (2010) with respect to the study of the Blue Nile. For instance,
70 Melesse et al. (2010) presents the low and high flow characteristics of the Blue

71 Nile River using wavelets and applies GRACE products to analyse moisture
72 flux.

73 One of the major challenges in applying the GRACE products to estimate
74 TWS changes over Ethiopian basins is the fact that only 2 out of the 12 basins
75 (Abbay and Wabishebele) can barely fulfill the requirement for the smallest re-
76 solvable basin area of 200,000 km² (see also [Tapley et al., 2004](#)). Furthermore,
77 [Longuevergne et al. \(2010\)](#) have pointed out that an accurate estimate of TWS
78 changes in small basins using GRACE-derived products requires a compromise
79 between competing needs for noise suppression and spatial resolution. To over-
80 come the spatial limitations, in the current study, Ethiopia was divided into ten
81 regions of equal sizes of 4° x 4°. For each region, TWS were computed from
82 GRACE data using the approaches presented in ([Wahr et al., 1998](#)).

83 This contribution focuses on the remotely-sensed TWS changes over Ethiopia
84 using GRACE products. For the purpose of evaluating GRACE products, the
85 study also uses rainfall and soil moisture data based on products from the Trop-
86 ical Rainfall Measuring Mission (TRMM) ([Kummerow et al., 1998](#)) and the
87 Global Land Data Assimilation System (GLDAS) ([Rodell et al., 2004](#)), respec-
88 tively. The major aims of the current study are: i) understanding the response
89 of Ethiopian aquifers to TWS changes from information obtained following the
90 analysis of inter-annual (i.e., between years variability), and intra-annual (i.e.,
91 processes that occur on a time scale of less than one year, but more than one
92 month) GRACE products, ii) depicting the reaction of each region to hydrolog-
93 ical input (rainfall) including any time delays, and iii) identifying the dominant
94 pattern of intra-annual, annual, and seasonal variability over Ethiopia by apply-
95 ing the statistical method of Principal Component Analysis (PCA) on GRACE-
96 derived TWS, soil moisture, and rainfall patterns. Knowledge of the lag time is
97 important for understanding the longest period over which the available stored
98 groundwater can be sustainably exploited after rainy seasons.

99 The remainder of this study is organized as follows; in section 2, the study
100 area and its characteristics are discussed. Section 3 presents the data used
101 and the employed analysis methods. The results are presented and discussed

102 in sections 4 and 5, respectively, and finally, section 6 summarizes the major
103 findings of this study.

104 2. Study Area

105 2.1. Location

106 Ethiopia, located between latitudes $3^{\circ}15'$ N to 15° N and longitudes 33° E to
107 48° E, is a landlocked country bounded by Eritrea (North), South Sudan (South
108 West), Sudan (North West), Kenya (South), Somalia (East) and Djibouti (North
109 East), with a surface area of 1,127,127 km². Its altitude ranges from nearly 120
110 m below mean sea level in the Dallol depression to about 4620 m above mean sea
111 level at Mount Ras Dashen. It contains three major physiographic regions that
112 include the western highlands and associated lowlands, the eastern highlands
113 and associated lowlands, and the rift valley in between them, running from
114 north-east to south-west, separating the eastern and western highlands (Fig. 1).
115 It is because of these physiographic influences on the drainage systems that
116 Ethiopia is counted as the water tower of East Africa, with twelve major basins;
117 eight of which are river basins, one is a lake basin, and the remaining three are
118 dry basins with no or insignificant out flow (FAO, 2005).

119 Ethiopia contributes to three major drainage systems (Fig 1), the Mediter-
120 ranean Sea drainage system (Abbay, Blue Nile, Baro-Akobo, Mereb and Tekeze),
121 the Great East African Rift-Valley drainage system (Omo-Ghibe, Awash, Rift-
122 Valley Lakes, Danakil and Aysha) and the Indian Ocean drainage system (Genale-
123 Dawa, Wabishebele and Ogaden). The groundwater resources of Ethiopia and
124 their distribution vary depending on their respective geological, structural, and
125 climatic conditions. The near-surface geological pattern that mainly govern the
126 hydrogeological characteristics of Ethiopia constitutes the region's oldest base-
127 ment rocks (Precambrian basement) (18%), Paleozoic and Mesozoic sedimentary
128 rocks (25%), Tertiary volcanic (40%), and Quaternary sediments and volcanics
129 (17%) (Alemayehu, 2006). It should be pointed out that there are also large
130 areas with Tertiary sediments occurring mainly in the rift valley.

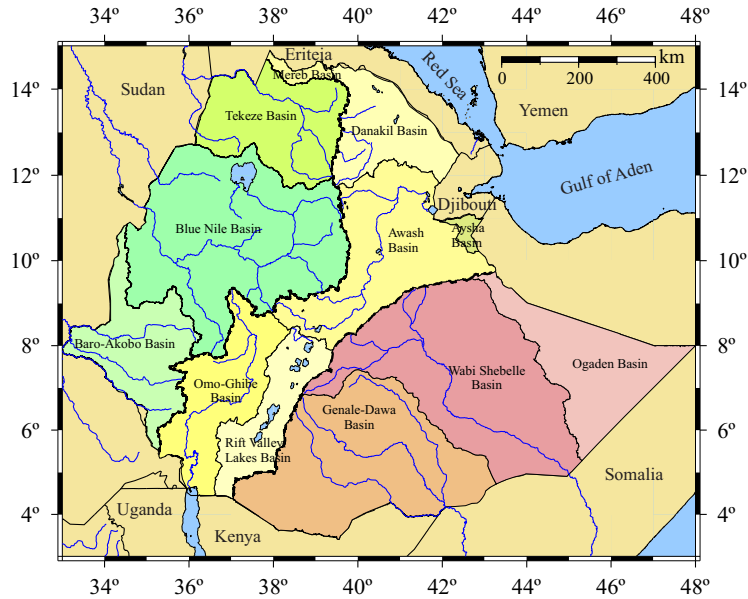


Figure 1: Major rivers and basins in Ethiopia. The black dashed line represents the major water divides between the Mediterranean Sea Basin (West), the Rift Valley endorheic basins (centre), and Indian Ocean Basin (East). Source: Modified from Nyssen et al. (2010). The different colours mark out the separate basins.

131 *2.2. Climate*

132 The climate of Ethiopia ranges from equatorial rainforest in the south and
 133 southwest, which is characterized by high rainfall and humidity; afro-alpine
 134 conditions on the summits of the Semien (western highlands) and Bale (east-
 135 ern highlands) mountains, to the desert-like conditions of the Northeast, East
 136 and Southeast lowlands. The temperatures range from 60 °C at the Dallol de-
 137 pression, to freezing temperatures on the Mount Ras Dashen Plateau (MoWE,
 138 2012). The mean annual rainfall varies from 3000 mm at Masha in the west-
 139 ern highlands to barely 200 mm in the eastern lowlands (Engida & Esteves,
 140 2011; Romilly & Gebremichael, 2011; Seleshi & Zanke, 2004). Ethiopia experi-
 141 ences two rainfall seasons. The major rainy season (summer, regionally know
 142 as “Kiremt”) extends from June to September, and accounts for nearly 60%
 143 (Segele et al., 2009), especially over the northern two thirds of the country.

144 The minor rainy season (spring, regionally know as “Belg”) usually begins in
 145 January/February and ends in April/May (Chukalla et al., 2013). In general
 146 rainfall over Ethiopia is influenced by both local scale forcing mechanisms as-
 147 sociated with the Ethiopian Highlands as well as heterogeneous land surface
 148 characteristics. In addition, the rainfall variability is significantly influences
 149 by large (global) atmospheric circulation and sea surface temperatures. These
 150 large scale forcing mechanisms are normally expressed through El Nino South-
 151 ern Oscillation (ENSO) induced anomalies, Quasi-Biennial Oscillation (QBO),
 152 as well as west-east sea surface temperature gradients over the equatorial In-
 153 dian Ocean (e.g., Bewket & Conway, 2007; Segeke et al., 2009). Table 1 shows
 154 the annual precipitation and potential evapotranspiration (ET) over the seven
 155 climatic zones over Ethiopia (Table 3 of Berhanu et al., 2013).

Table 1: Annual precipitation, average temperature, and potential evapotranspiration (ET)
 (Source: adapted from Berhanu et al. (2013)).

Climatic zones	Annual precipitation (mm)	Temperature (°C)	Annual ET (mm)
Arid	<302	>27.5	2159
Semi-arid	302-350	27.5-21	1737-2159
Sub-moist	350-566	21-16	1431-1737
Moist	566-835	16-11	1124-1431
Sub-humid	835-1189	11-7.2	895-1124
Humid	1189-1711	<7.5	<895
Per-humid	>1711	-	-

156 The common indicators of climate variability and changes are trends in pre-
 157 cipitation and the maximum and minimum temperatures. Mengistu et al. (2013)
 158 reported a consistent warming trend in the maximum and minimum tempera-
 159 tures over the past few decades in Ethiopia. However, rainfall shows a declining
 160 trend for the east, south and southwest parts of Ethiopia (Seleshi & Zanke,
 161 2004). Additionally, for the central highlands, there is no evidence of trend in

162 rainfall (Cheung et al., 2008). In general, there is no trend in the extremes of
163 seasonal rainfall in *Kiremt* and *Belg* over Ethiopia (cf., Seleshi & Camberlin,
164 2006). However, Marshall et al. (2012) have reported a gradual decline in evap-
165 otranspiration on the order of 5 mm/year over the coast of West Africa, the
166 Sahel, and the western Ethiopian highlands, over a 31 years study period.

167 3. Datasets and Methodology

168 3.1. Data

169 (i) *Gravity Recovery and Climate Experiment (GRACE) Data:*
170 GRACE, a US/German satellite gravimetry mission that tracks changes in the
171 Earth’s gravity field (Tapley et al., 2004) has been the most commonly exploited
172 satellite in the past decade for computing TWS. GRACE products have been
173 used to quantify water storage changes at regional as well as global scales as
174 reported for different regions (e.g., Awange et al., 2008; Forootan et al., 2012,
175 2014; Rodell et al., 2007). The GRACE Release-05 (RL05) Level-2 (L2) dataset
176 provides the processed time-variable gravity field products applied in this study.
177 The products are provided as sets of spherical harmonic coefficients (Stokes’s
178 coefficients) averaged over certain time periods (usually monthly). Spherical
179 harmonic coefficients at high degrees are affected by correlated noise (Kusche,
180 2007; Kusche et al., 2009) that need to be smoothed before being used for the hy-
181 drological analysis in this study. These correlations can be reduced, using either
182 an empirical method based on a polynomial fit (e.g. Swenson & Wahr, 2006), or
183 an *a priori* synthetic model of the observation geometry (e.g., Kusche, 2007).
184 In this regard, the present study employed the DDK3 (Kusche et al., 2009)
185 filtered monthly spherical harmonic coefficients dataset available from the of-
186 ficial website of the International Centre for Global Earth Models (ICGEM)
187 (<http://icgem.gfz-potsdam.de/ICGEM/TimeSeries.html>). The suitability
188 of the employed DDK filter is discussed, e.g., in Werth et al. (2009). Our
189 investigations covered the period from January 2003 to December 2011, and
190 included 96 months of the German GeoForschungsZentrum (GFZ), Potsdam,

191 products.

192

193 (ii) *Global Land Data Assimilation System (GLDAS)*:

194 GLDAS model is developed jointly by the National Aeronautics and Space
195 Administration (NASA), the National Oceanic and Atmospheric Administra-
196 tion (NOAA), and the National Centers for Environmental Prediction (NCEP)
197 (Rodell et al., 2004). It drives multiple offline (not coupled to the atmosphere)
198 land surface models that integrate huge quantities of observation-based data.
199 GLDAS executes its outputs globally at a relatively high spatial and temporal
200 resolution, enabled by the Land Information System (LIS) (Fang et al., 2009).
201 The parameters in the GLDAS-monthly data fall into three main categories:
202 water balance, energy balance, and forcing parameters. Water balance includes
203 soil moisture parameters and other variables such as rainfall rate and surface
204 runoff. To investigate the spatial and temporal variation of soil moisture over
205 Ethiopia, we used the water balance monthly soil moisture data generated by
206 NOAH LSM at a spatial resolution of $1^\circ \times 1^\circ$. The data was obtained freely from
207 NASA, Goddard Earth Science Data and Information Services Center (GES
208 DISC) (<http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings>).

209

210 (iii) *Tropical Rainfall Measuring Mission (TRMM) Satellite Rainfall*:

211 TRMM, a joint USA/Japan satellite mission, is designed to survey the rain
212 structure, rate, and distribution in tropical and subtropical regions (latitude
213 range $\pm 50^\circ$) (Kummerow et al., 1998). Amongst the TRMM precipitation
214 products are those derived from integrated rainfall estimates from various sen-
215 sors on-board satellites such as Precipitation Radar (PR), Special Sensor Mi-
216 crowave Imager (SSM/I), infra-red (IR) data from geostationary satellites, and
217 additional merged rain gauge observations (Liu et al., 2012; Huffman et al.,
218 2007). TRMM-3B42 version version 7 (Huffman & Bolvin, 2012), which was
219 made available to the public on 22 May, 2012. It has a spatial resolution of
220 $0.25^\circ \times 0.25^\circ$ and temporal resolution of 3-hour. The major difference between
221 the previous versions and the one used in this study is that the later has an

222 improved scheme for weighting the incorporated rain-gauge data (Huffman &
223 Bolvin, 2012; Fleming & Awange, 2013). The data was obtained from NASA
224 GES DISC (<http://mirador.gsfc.nasa.gov/>).

225 Our motivation for selecting TRMM satellite data for this study is informed
226 by the works of Dinku et al. (2007, 2008, 2010), and Beyene & Meissner (2010)
227 in terms of the validation of satellite products in the region, which includes
228 nearly half of Ethiopia (i.e., the Blue Nile portion). In particular, Dinku et al.
229 (2010) reported the fairly good performance of the TRMM-3B42 rainfall product
230 compared to locally available rain gauge data. It should be pointed out that
231 although another product, TRMM-3B43, provides monthly data, we used the
232 shorter daily TRMM-3B42 product mainly due to the fact that these have been
233 validated in the region (see, e.g., Dinku et al., 2010).

234 *3.2. Methods*

235 As already stated, GRACE products are limited in their usefulness to a
236 spatial extent of greater than 200,000 km². On the one hand, only two of the
237 Ethiopian basins (Abbay and Wabishebele) can fulfill this criterion. On the
238 other hand, Ethiopian catchments exhibit very different characteristics as they
239 are climatically and environmentally extremely heterogeneous (see Section 2).
240 In this respect, computing the TWS over Ethiopia as a whole might lead to
241 wrong conclusions, since the basins' averages will follow the general variability
242 of the area with the dominant signal. To overcome this problem, Ethiopia was
243 subdivided into 4° x 4° (approximately 440 km x 440 km, i.e., 193,000 km²)
244 blocks that enable (i) the spatial extent required for the valid consideration of
245 the GRACE products, and (ii) minimizing the errors that might result from gen-
246 eralizing products for Ethiopia as a whole. This way, ten regions are obtained,
247 whose minimum/maximum latitude and longitude, and designation to be used
248 in this paper from now on are shown in Fig. 2. These subdivisions are made
249 in such a way that larger physiographic regions of Ethiopia are represented as
250 close as possible. Since GRACE data sets have already been smoothed using the
251 DDK3 filter (Kusche et al., 2009), the computation of GRACE-derived TWS is

252 undertaken following the approach presented in [Wahr et al. \(1998\)](#). For all 10
253 regions (Fig. 2), TWS values were generated with an approximate monthly tem-
254 poral resolution over the study period (2003-2011), where the average field from
255 the study period (2003-2011) was removed from the monthly TWS. The missing
256 data from June 2003 was filled using a simple linear interpolation. The average
257 error of the derived TWS over the whole region of the study was estimated to
258 be less than 5 mm of water columns. This error was estimated using the formal
259 errors of the Stokes coefficients smoothed using DDK3 filter and converted to
260 TWS (cf. [Wahr et al., 1998](#)).

261 Monthly soil moisture down to 2 m beneath the surface has been computed
262 from NOAA Land Surface Model (LSM) and water budget data obtained for four
263 layers (0-10 cm, 10-40 cm, 40-100 cm and 100-200 cm), with spatial resolutions
264 of $1^\circ \times 1^\circ$ and aggregated to a spatial domain of $4^\circ \times 4^\circ$. The average rainfall
265 over each study region obtained from TRMM-3B42 was also rescaled to $4^\circ \times 4^\circ$
266 and a monthly temporal resolution. Since the TRMM 3B42-V7 rainfall rate are
267 3-hourly averages centered at the middle of each 3-hour period (i.e., 0 h, 3 h, 6
268 h, 9 h, 12 h, 15 h, 18 h, and 21 h), they are converted to total daily rainfall by
269 first multiplying each 3-hourly rainfall rate by 3 to get the total rainfall for each
270 3-hour period, then added to obtain the desired monthly data, the sum of all
271 the 3-hourly total rainfalls in within 24-hour period is multiplied by the number
272 of the days for a specific month. Both TRMM and GLDAS data were filtered
273 using a Gaussian filter of 300 km radius. The radius of 300 km was selected
274 to be consistent with the smoothing impact of the DDK3 filter applied to the
275 GRACE products. This value has been tested, e.g., in [Werth et al. \(2009\)](#) and
276 was found to be applicable to nearly all river basins.

277 (i) *Deriving Changes in Groundwater from GRACE and GLDAS:*

278 The most important variables to use when deriving groundwater storage changes
279 (GW) from GRACE-TWS data are; (i) changes in surface water storage (SWS)
280 associated with lakes and reservoirs, (ii) changes in soil moisture (SM) and
281 (iii) changes in snow water equivalent (SWE). However, when compared to the
282 land surface, only about 0.7% of Ethiopia is covered by water bodies ([MoWE,](#)

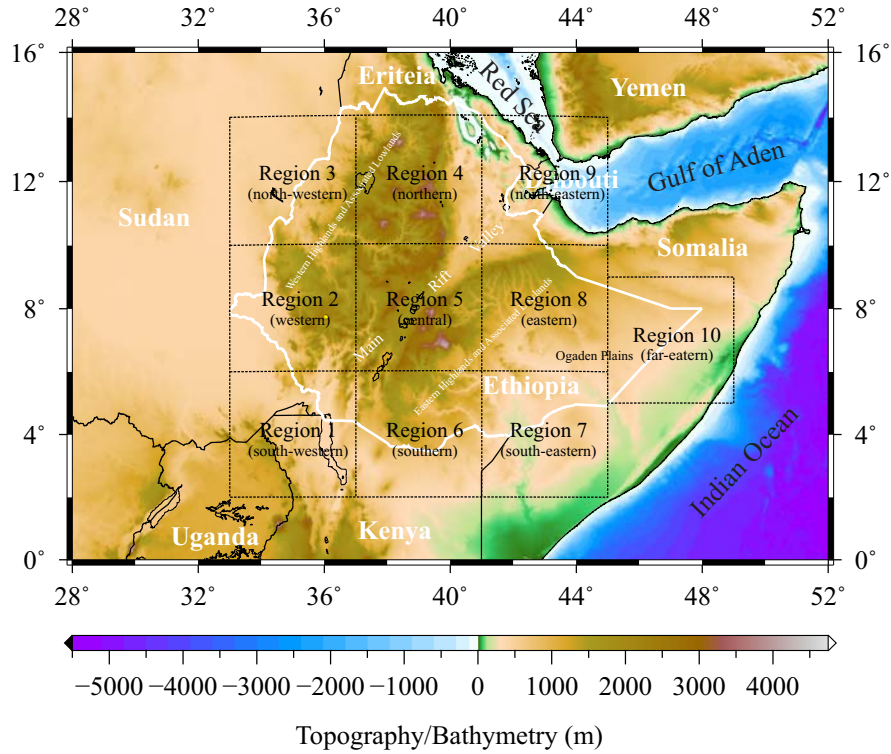


Figure 2: Ethiopia is divided into ten study regions of 4 degree by 4 degree to meet the spatial extent requirement of the GRACE products of 200,000 km² and the physiographic regions.

283 2012). Therefore, we did not consider the contribution of surface water storage
 284 in computing TWS over Ethiopian regions since the areas of the existing water
 285 bodies and their fluctuations levels were quite small. The snow water equivalent
 286 was also not considered in our computation since its temporal variability over
 287 Ethiopia is negligible compared to the other contributors of TWS. Soil moisture
 288 anomalies were computed by removing the mean value over the extent of the
 289 study period (2003-2011) of the monthly soil moisture values. The monthly
 290 groundwater anomaly (ΔGW) was then obtained by subtracting changes in soil
 291 moisture from TWS changes as:

$$GW = TWS - SM, \quad (1)$$

292 assuming that the surface water and snow are insignificant. This approach has
 293 been previously applied by [Rodell et al. \(2009\)](#) in Northern India with the aim
 294 of estimating groundwater depletion.

295 In association with the GRACE-derived TWS estimates over the study re-
 296 gion, [Bonsor et al. \(2010\)](#) used a recharge model for the Nile Basin, Zoomable
 297 Object Oriented Distributed Recharge Model (ZOODRM), to interpret the sea-
 298 sonal variation in TWS. They found that the simulated annual variation in
 299 groundwater storage and soil moisture accounts for 50-90% of the variations in
 300 the GRACE-derived TWS.

301 (ii) *Total Water Storage Duration Curve (TDC) and Total Storage Deficit*
 302 *(TSD):*

303 To simplify the information available for judging the characteristics of TWS, we
 304 express the TWS changes as a single value through the use of the TWS duration
 305 curve (TDC). The TDC is derived through the principle of the Flow Duration
 306 Curve (FDC). The FDC is a frequency distribution formed from daily/monthly
 307 stream flow data and their exceedence probability ([Yadav et al., 2007](#)). In this
 308 approach, all the available data are first listed in descending order and given
 309 a rank (the maximum will take the value 1 and the minimum will take the
 310 last rank). Using the ranks m , the probability of exceedence (in percentage) is
 311 computed using the Weibul method ([Helsel & Hirsch, 2002](#), p. 23):

$$Exceedence\% = \frac{m}{(N + 1)} \times 100, \quad (2)$$

312 where m is rank and N is the sample size. TDC is obtained by plotting the
 313 TWS against its probability of exceedence. The slope S_{TDC} of the TDC is then
 314 calculated between the 33rd and 66th TWS percentiles using

$$S_{TDC} = \frac{TWS(33\%) - TWS(66\%)}{66 - 33} \quad (3)$$

315 modified for the TWS case from [Sawicz et al. \(2011\)](#) as this portion represents
 316 a relatively linear part of the TDC. This slope reflects the aquifer storage size
 317 and the aquifer through flow property.

318 To infer on the TWS depletion, Total Storage Deficit Index (TSDI) for each
 319 region was computed from GRACE derived TWS anomalies as (Yirdaw et al.,
 320 2008):

$$TSD_j = \frac{TWS_j - \text{Mean}(TWS_j)}{\text{Max}(TWS_j) - \text{Min}(TWS_j)} \times 100, \quad (4)$$

321 where TDS_j is the total storage deficit (%); TWS_j is the monthly total storage
 322 anomaly as derived from GRACE-measurements, $\text{Mean}(TWS_j)$, $\text{Max}(TWS_j)$,
 323 and $\text{Min}(TWS_j)$ are the long term mean, maximum, and minimum TWS , re-
 324 spectively, for each month j over the study period (2003-2011).

325 (iii) *Cross-correlation Analysis*:

326 To study the lag time of water storage variations (TWS and soil moisture) in
 327 response to rainfall, lagged correlation analyses at 95% confidence level were car-
 328 ried out between (a) TWS and rainfall, (b) soil moisture variation and rainfall,
 329 and (c) soil moisture anomalies and TWS.

330 (iv) *Principal Component Analysis (PCA)*:

331 Principal Component Analysis (PCA) is a statistical technique that can be used
 332 to extract dominant uncorrelated patterns from spatio-temporal observations
 333 (Preisendorfer, 1988). In principle, PCA expands the derived TWS changes
 334 within the 10 defined regions in terms of new sets of orthogonal vectors know as
 335 empirical orthogonal functions (EOFs) associated with their uncorrelated tem-
 336 poral evolutions known as principal components (PCs) (Frootan & Kusche,
 337 2012). The PCA method used in this paper is based on the eigenvalue decom-
 338 position of the data-derived auto-covariance matrix (Preisendorfer, 1988). In
 339 this study, only the dominant components of TWS behaviour over Ethiopia are
 340 shown. The less dominant components that most often correspond to lower
 341 correlations with overall TWS changes are not presented. To decide on the
 342 significant number of modes, North's rule of thumb, which states that if the
 343 sampling error of a particular eigenvalue is comparable to a nearby eigenvalue,
 344 then the sampling errors in the EOF will be comparable to the "nearby" EOF
 345 (North et al., 1982) was used (see Preisendorfer (1988) for details).

346 4. Results

347 Figure 3 shows box plots used to highlight the overall patterns of response
348 for the variations in water storage over Ethiopia computed from GRACE, soil
349 moisture (from GLDAS), and rainfall (from TRMM) for the 10 sub-regions over
350 the study period (2003-2011). The lower whisker of the box plot indicates the
351 lowest observed value (sample minimum), the lower end of the box is the lower
352 quartile (25%), the line across the box indicates the median, the upper end of
353 the box specify the upper quartile (75%), and the upper whisker of the plot
354 illustrates the highest observed value of the sample. The red crosses indicate
355 outliers that represent cases that have values more than three times the height
356 of the boxes. Overall, the results in Fig. 3 (top) show that the variation in
357 TWS is greatest in the western highlands area (see Fig. 1), i.e., western (region
358 2), north-western (region 3), and northern (region 4) of Ethiopia, while the far
359 eastern corner (region 10) shows relatively low variation. Highland dominated
360 regions (Fig. 3, middle and bottom, regions 2, 3, 4 and 5) show strong variations
361 in soil moisture and rainfall, while the lowland dominated segments display
362 comparatively less variability (Fig. 3, middle and bottom).

363 4.1. Dominant Variability of Water-Storage over Ethiopia

364 The PCA method was applied to the TWS, soil-moisture, and precipita-
365 tion fields derived for the 10 sub-regions (Fig. 4) in order to identify patterns
366 of simultaneous temporal variations in the whole country rather than any lo-
367 calization of the signal.. Applying North's rule of thumb shows that for the
368 three data sets above, only the first two components are statistically significant,
369 which are shown in Fig. 4. The first mode of PCA on TWS (EOF1 and PC1)
370 is equivalent to 65.83% of total TWS variability, with PC1 showing a dominant
371 annual variability and EOF1 showing that regions 2, 3, 4 and 5 are the domi-
372 nant. Note that the PCA/EOF results are somewhat close to the regions that
373 show predominant variability shown in Fig. 3a, as one could expect. The same
374 statement is also true for the first mode of soil-moisture (67.4% of variance) and

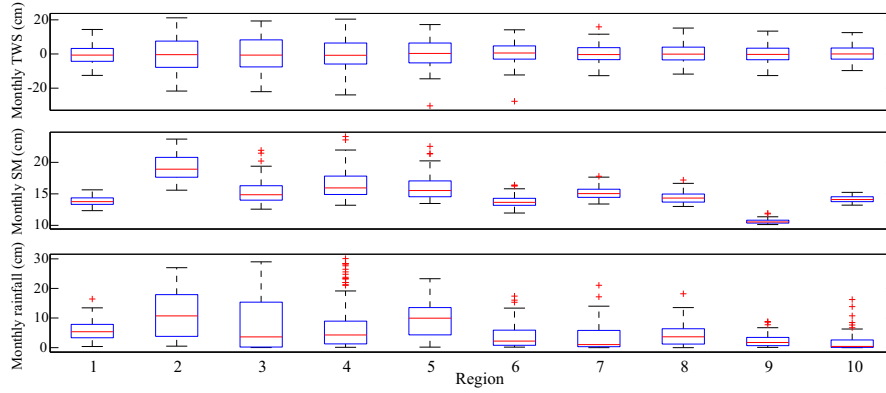


Figure 3: Summary of TWS, soil moisture, and rainfall variability for each of the Ethiopian region shown in Fig. 2. The red crosses indicates outliers. TWS (top) is seen to be greatest in western (region 2), north-western (region 3) and northern (region 4) region and less so in the far east (region 10). Regions 2, 3, 4 and 5 (central) show a strong variation in soil moisture (middle) and rainfall (bottom).

375 rainfall (70.1% of variance). The second modes of all three data sets extract
 376 mostly inter-annual variability in the data. There are also some annual and
 377 intra-annual variations detectable in the second modes, which are due to the
 378 incapability of the PCA method to perfectly separate such signals (Forootan &
 379 Kusche, 2012).

380 The second mode (EOF2 and PC2) of the TWS (Fig 4) is equivalent to 14.9%
 381 of the total variance and shows that the regions 2, 3, 6, 7, 8 and 9 are dominant.
 382 The dominant inter-annual soil moisture variations are found in regions 1, 2, 5-
 383 8, and 10 (EOF2 and PC2 of soil-moisture in Fig. 4, middle). Finally, the same
 384 regions, i.e., 1, 2, 5-8, and 10 are also found to exhibit the most inter-annual
 385 precipitation (EOF2 and PC2 of rainfall in Fig. 4, right), again confirming
 386 our findings in Fig. 3a. We should mention that the accuracy of the annual
 387 and semi-annual GRACE-TWS estimations are around 1 cm (in amplitude)
 388 for the selected $4^{\circ} \times 4^{\circ}$ regions. This has also been tested by considering the
 389 sampling errors originating from length-limited data sets (Preisendorfer, 1988,
 390 p. 199), as well as the coefficients errors, provided by the data producer, the

391 GFZ Potsdam Centre (the error-bars are not shown here in order to enhance
the visual interpretation of the patterns).

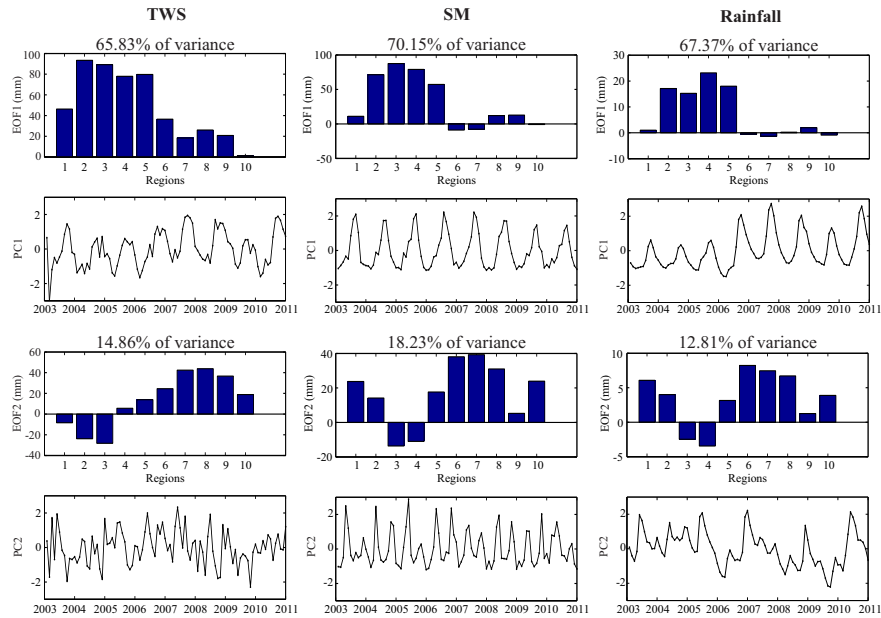


Figure 4: Results of PCA, derived from its application to time series of the 10 predefined regions in Fig. 2. TWS data from GRACE (left), soil moisture data from GLDAS (middle) and, rainfall data from TRMM (right).

392

393 4.2. Annual and Seasonal Mean TWS Changes

394 Figure 5 depicts the mean water mass lost or gained in cm/month aggregated
395 over seasonal and annual time scales from monthly GRACE-derived TWS values
396 over the study period. The results of the seasonal analysis of TWS show regions
397 1, 2, 3, 4 and 5 having the same characteristics, where they experienced a
398 decrease in TWS during winter and spring and gained it during summer and
399 autumn. Regions 7 and 8 reflect the same characteristics as the first group, but
400 differ in that their main water loss season is during winter and the water gain
401 in summer (Fig. 5, top). The other three regions (region 6, 9, and 10) have
402 different characteristics from all the others. The only characteristic that regions

403 6 and 10 have in common is that they gain water mass for 75% of the year (i.e.,
 404 3 seasons), while it is 50% for region 9. Our results, from both GLDAS and
 405 GRACE products, confirm the fact that summer is the main water gain season
 for Ethiopia corresponding to the main rainy season.

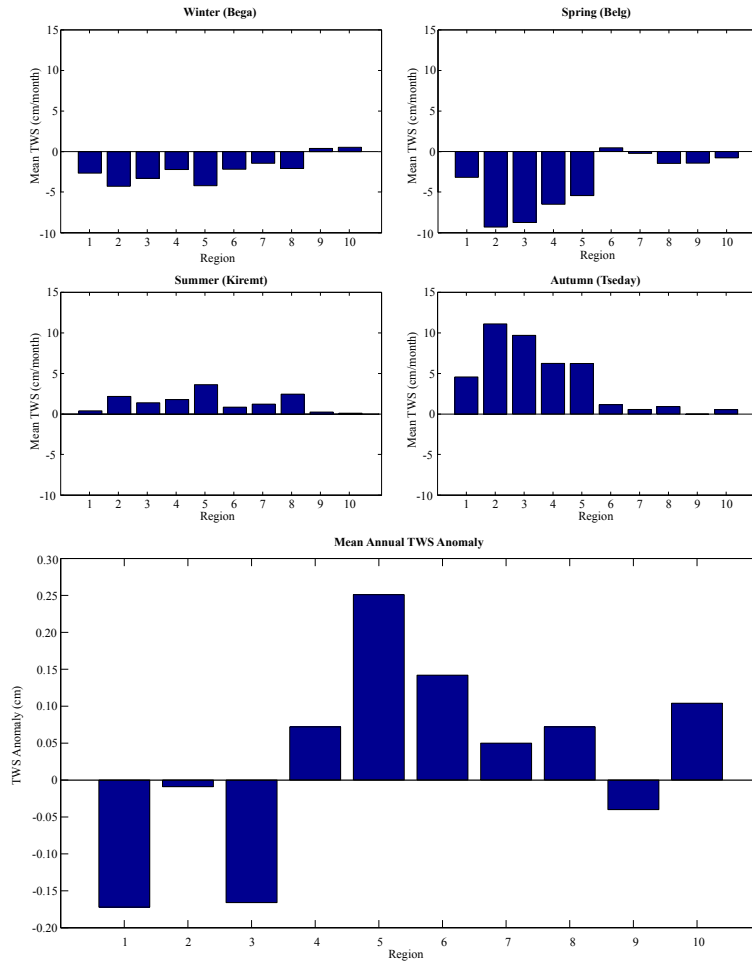


Figure 5: Seasonal (top) and Annual (bottom) means of TWS variation over Ethiopia derived from GRACE product for the study period (2003-2011). In brackets are the Ethiopian names for the seasons, Bega (December-February), Belg (March–May), Kiremt (June-August) and Tseday (September-November), see Section 2.

406

407 The annual mean indicates that mass has been gained in the northern (region

408 4), central and eastern (regions 5 and 8 respectively), southern (regions 6 and 7)
 409 and far eastern (region 10) regions, while the south-western (regions 1), western
 410 (region 2), north-western (region 3), and north-eastern (region 9) regions showed
 411 that mass has been lost (Fig. 5, bottom). The maximum mean annual water
 412 mass gains were recorded in central Ethiopia (region 5) during summer (Fig. 5),
 413 which may be attributed to three main factors. First, the larger part of the Rift
 414 Valley basin lakes lies in this region (see Figs. 1 and 2), and could be exerting a
 415 greater surface water influence. The Ethiopian rift valley lakes' basin (Fig. 1),
 416 which lies in the main Ethiopian Rift, is a collection of cascade lakes, which
 417 might have underground connections with other lakes. However, regarding the
 418 second factor, considering the amount of surface water, the rift valley lakes'
 419 basin is known to have a closed watershed, and as such there is water going
 420 into the lakes, but have no surface water outlets, e.g., Lake Naivasha (Awange
 421 et al., 2013a). Thirdly, the region is again the starting point of four of the six
 422 Ethiopian international basins that include the Awash, Omo-Ghibe, Ganale-
 423 Dawa and Wabishebele.

424 The GRACE-derived TWS duration curve (TDC, see Eqn. 2) is presented
 425 in Fig. 6. From the probability of exceedence at the no loss/no gain point (i.e.,
 426 point at which the TWS anomaly equals zero), it can be seen that almost all
 427 regions gained water mass only 45% of the time, and lost it 55% of the time.
 428 The TDC curves in Fig. 6 also allow us to reflect upon the probability of change
 429 in amount of TWS. For, example, the maximum water mass gain, which has a
 430 probability of occurrence of less than 1% over the study period, ranges from 12
 431 cm/month in region 10 to 21 cm/month in region 2, while the maximum water
 432 loss with a percentage exceedence of about 99% ranges from 30 cm/month in
 433 region 5 to 10 cm/month in region 10.

434 To quantify the TWS changes into a single value, the slope of the TDC was
 435 calculated using equation 4. A high slope value means rapid response and small
 436 storage potential, while a low slope value means slow response to incoming water
 437 mass and large storage potential. For simplicity, we can group the regions based
 438 on their TDC slopes as, i) $S_{TDC} > 30\%$ (only region 2), ii) $20\% < S_{TDC} < 30\%$

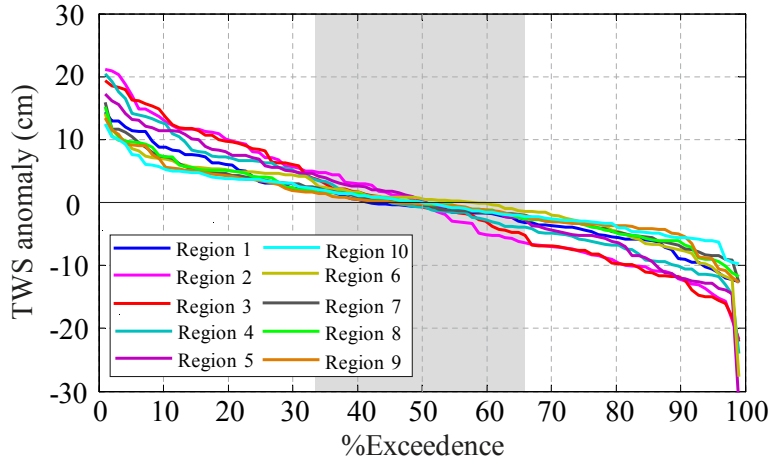


Figure 6: Total Duration Curve (TDC) of the GRACE-based monthly TWS anomalies over the study period. The figure indicates that almost all regions gained water 45% of the time. Slope analysis of this figure show that over Ethiopia, TWS changes are high in the western region and low in the eastern region. The extreme fall at the end of the curves for regions 5 and 6 could be the consequence of the loss of a large amount of water in January and February 2003, which was the result of drought that propagated from the previous year.

439 (regions 3, 4 and 5) and iii) $10\% < S_{TDC} < 20\%$ (regions 1, 6, 7, 8, 9 and 10).
 440 This indicates that over Ethiopia, the TWS changes are highest in the western
 441 region and lowest in the north-eastern region, i.e., consistent with the findings
 442 in Figs. 3 and 4.

443 4.3. Inter-annual Variation

444 Changes in TWS, soil moisture (SM), rainfall, and groundwater storage
 445 (GW) anomalies over the study period for each month have been compiled
 446 in Fig. 7. The year to year changes in TWS (Fig. 7(a)) shows that except
 447 for a few months, e.g., June (regions 1, 4 and 9), July (regions, 7 and 8) and
 448 September (region 6), there exist significant variability in TWS in all regions for
 449 each month. Figure 7(b) also show considerable variations in soil moisture for
 450 all months, where it is relatively strong during rainy seasons. The inter-annual
 451 plot of rainfall illustrated in Fig. 7(c) describes the considerable variation that
 452 exists in all months in regions 1 and 2, while regions 3-5, 8 and 9 show relatively

453 low variability except during the major rainy season (June-September; JJAS).
454 Additionally, there is a low variability in June-September for regions 6, 7 and
455 10, i.e., south east and east. The GW plots (Fig. 7(d)) present similar charac-
456 teristics as the soil moisture and TWS. From Fig. 7, the variations of TWS, SM
457 and GW anomalies are seen to be less correlated to rainfall for all regions with
458 the exception of region 2 (western), see also Fig. 11.

459 4.4. *Intra-annual Variation*

460 Figure 8 shows the intra-annual variability of TWS, soil moisture, GW and
461 rainfall developed from the mean of each month over the study period as opposed
462 to the red lines in Fig. 7. From this, one can clearly see two distinct groups
463 based on the behaviour of their TWS anomaly values over the months. The first
464 group includes regions 2, 3, 4 and 5, where the TWS and GW anomalies shows
465 three similar parts; i) the rising limb, which occurs from June to September,
466 indicating the recovery period of TWS, ii) the peak, which occurs in August, and
467 iii) the recession or falling limb that covers a longer period than the previous
468 ones, i.e., starting from a point at which the peak is attained and extending
469 up to June. The results indicate that, like the rainfall patterns, TWS shows
470 seasonality, having seasons showing mass gain (JJA and some parts of SON),
471 while in the other two seasons, the mass loss exceeds the gain in most regions of
472 Ethiopia. This happens since the mentioned periods are the main rainy seasons
473 in Ethiopia. The second group includes all the other regions with characteristics
474 opposite to the first group. That is, they have short duration recession curves
475 with very long recovery or rising limb period, attaining their maximum peaks
476 in the SON season. Despite the fact that SON is the long rainy period in these
477 regions, the length of the rising period might be attributed to the aquifer type
478 and size, as well as recharge mechanism. Compared to the rainfall, and the
479 response of GW and TWS, one can see that there appears to be very little
480 fluctuation in soil moisture in all cases.

481 Examining now the soil moisture in greater detail (Fig. 9), one can visually
482 identify extreme regions that include (i) the western part of Ethiopia (i.e., region

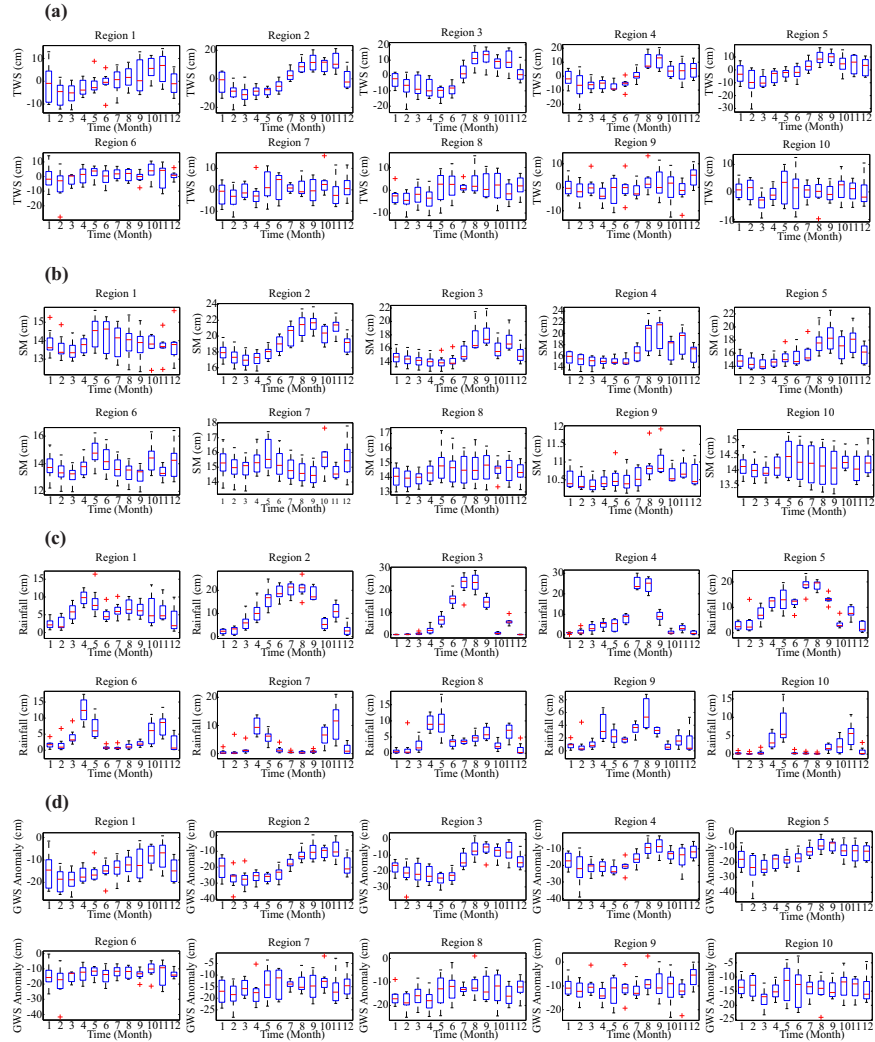


Figure 7: Inter-annual variability of TWS (a), Soil Moisture (b), Rainfall (c) and GW anomaly (d) over Ethiopia. The variation in TWS (a), soil moisture (b), and GW (d) are unrelated to the rainfall (c), thus indicating a possible human influence on hydrological changes in Ethiopia. Note the difference in amplitude of the figures. Although (a) and (d) look similar, they differ considerably in amplitude.

483 2), which has the highest soil moisture content of all the studied regions, (ii) the
 484 north-eastern (i.e., region 9), which has the lowest soil moisture content, and
 485 iii) the intermediate regions, which include all the other areas. Apart from this,

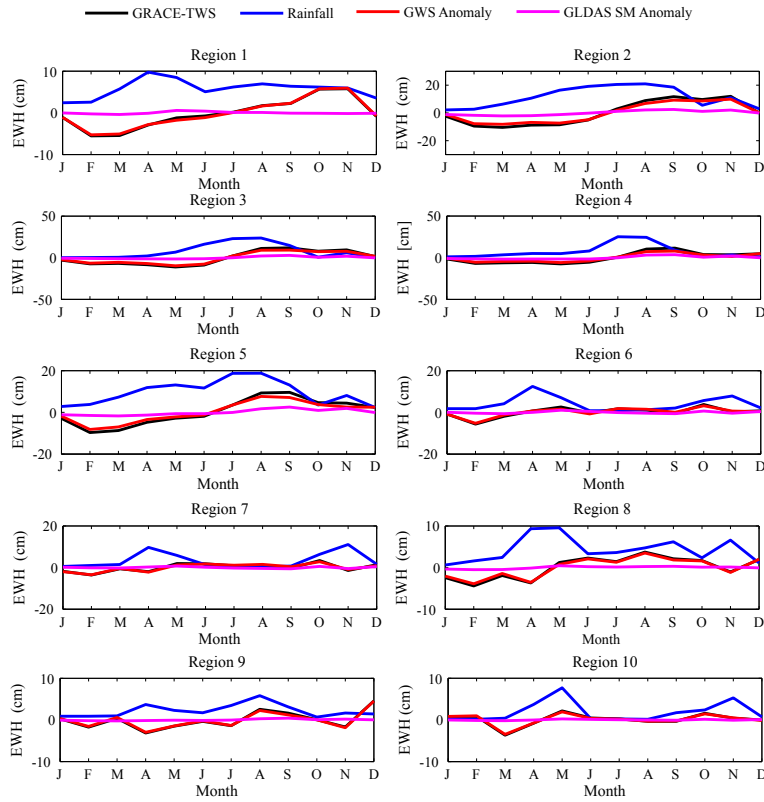


Figure 8: Intra-annual variability of the TWS, SM, GW and rainfall EWH (equivalent water height) over Ethiopia.

486 Ethiopia may be classified into three soil moisture variability regions. The first
 487 covers the western (region 2), north-western (region 3), northern (region 4) and
 488 central (region 5) sub-regions, which show little variability over the first half of
 489 the year, and then a significant rise in the second half, attaining their peaks in
 490 September. This is because the second half of the year is the main rainy season
 491 for most segments. The second soil moisture region (southern; region 6 and
 492 south-eastern; region 7) is characterized by the occurrence of two small peaks,
 493 one in May and the other in November, while the third soil moisture region
 494 includes the south-western (region 1) and eastern (region 10), displaying very
 495 little variability in soil moisture throughout the year compared to others.

496 The soil moisture variation over Ethiopia bears a resemblance to the agro-

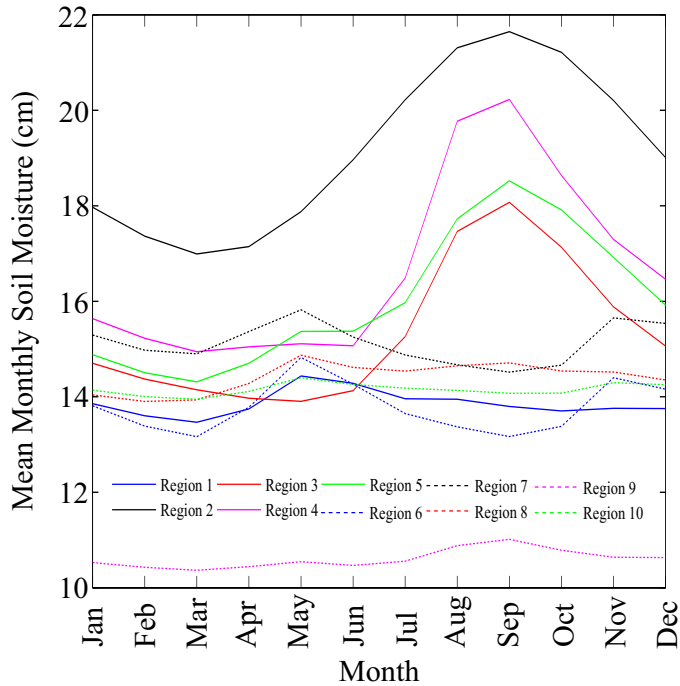


Figure 9: Intra-annual variability of soil moisture over Ethiopia.

497 ecological zonation described in [Hurni \(1988\)](#). Depending on the dominant
 498 agro-ecological zone in each region, three sub-divisions may exist. These are;
 499 (i) Dega/Woyna Dega consisting of regions 2, 4 and 5, (ii) the Bereha made
 500 up of regions 1, 6, 7, 8, 9 and 10, and (iii) the transitional zone Kolla/Dega,
 501 comprised only of region 3. The Dega/Woyna Dega group displays high soil
 502 moisture levels with strong seasonality, while the Bereha group shows little
 503 seasonality behavior as they receive little rainfall. Furthermore, Fig. 9 indicates
 504 two regions of comparatively extreme wetness and dryness, i.e., regions 2 and
 505 9, respectively. The possible reason for region 2's wetness is the fact that i) this
 506 region receives rainfall almost throughout the year, comprising the area which
 507 obtains the highest annual rainfall amount in Ethiopia (see section 2) and, ii)
 508 the land cover in the region is highly dominated by rainforest. In region 9, the
 509 Danakil depression region, which shows much lower soil moisture content, is
 510 known to be one of the driest regions of Ethiopia, where there is no significant

511 river flow and only short period bimodal rainfall, very scarce vegetation cover,
512 and high temperatures (see Section 2). Ertale, the area where volcanic magma
513 can be seen at Earth's surface is also in this region, where high temperatures,
514 combined with little rainfall, lead to the retention time of water in the soil to
515 be very limited.

516 *4.5. Correlation between Different Data Sets*

517 A correlation analysis between available data sets was made using the mean
518 monthly data and is presented in Fig. 10 to study the time lag between rainfall
519 and TWS, soil moisture and TWS, and soil moisture and rainfall. The analysis
520 shows almost no lag between soil moisture and TWS in all regions, except
521 regions 1 and 9, where lags of 5 and 1 month, respectively are seen. For TWS
522 and rainfall, lags of 0 (region 10), 1 month (regions 4 and 7), 2 months (region
523 3), 3 months (regions 2, 5 and 8), 4 months (region 9), and 6 months (regions
524 1 and 6) have been observed, with strong correlations in regions 2, 3, 4 and
525 5. The lags between TWS and rainfall obtained from Fig. 10 are tabulated in
526 Table 2. Larger lag periods are indicative of water-storages properties such as
527 large groundwater reservoirs, indirect recharge mechanisms, or a combination
528 of both, while smaller values are more likely to be attributed to direct recharge
529 mechanisms, smaller groundwater reservoir or again a combination of them.

530 *4.6. Relationship between TRMM-Rainfall and GRACE-TWS*

531 From Figs. 7 and 8, one can see that there is little significant delineation
532 between the plots of TWS and GW. It is, therefore, thought that the very
533 large influence of TWS over Ethiopia comes from the groundwater storage. The
534 relationship between rainfall and TWS is presented in Fig. 11. This is developed
535 by accounting for the lag duration of TWS from rainfall. For example, in region
536 1, a lag of 6 months is used to assess how much of the rainfall observed in
537 January contributed to the TWS in July. In all regions, except 2, 4 and 5,
538 coefficients of determinant R^2 of less than 0.5 were obtained. For these regions,
539 where high values of R^2 are obtained, i.e., the western (region 2), northern

Table 2: Recharge mechanisms, recharge rates, hydrogeology, aquifer flow, and storage type characteristics over different regions of Ethiopia (Source: [Abiye \(2010\)](#); [Chernet \(1993\)](#)). The Table also includes the slope m of the TDC derived from GRACE-TWS for each region and the lag between GRACE-TWS and TRMM-rainfall.

Region	Recharge Mechanisms	Recharge rate (mm/yr)	GRACE-mean annual TWS (mm/yr)	Hydrogeologic Setting	Aquifer flow and storage type	TDC slope (m)	Lag (months)
1	Recharge from wadi beds through local wadi floods	50-150	-26.64	Unconsolidated sediment.	Inter-granular	-0.15	6
2	Direct diffuse recharge through soil and root zone. Recharge from wetland during high flood	150-250	-1.08	Volcanic rocks, metamorphic rocks and intrusives.	Fracture	-0.344	3
3	Wadi bed through local wadi floods, Selective recharge from heavy rainfall	50-150	-19.92	Volcanic and metamorphic rocks and intrusives.	Fracture	-0.276	2
4	Selective recharges from heavy rain falls, direct diffuse + floods from highlands	50-150	8.64	Metamorphic rocks and intrusives.	Fracture	-0.236	1
5	Selective recharges from heavy rain falls, Mountain block and mountain font	50-250	30.12	Metamorphic rocks and intrusives.	Fracture	-0.221	3
6	Selective recharges from heavy rainfalls wadi beds through local wadi floods	50-150	17.04	Metamorphic rocks and intrusives, consolidated sediments.	Inter-granular	-0.146	6
7	Selective recharges from heavy rainfalls wadi beds through local wadi floods	<50	6.00	Consolidated sediments.	Inter-granular and Fracture	-0.136	1
8	Selective recharges from heavy rainfalls wadi beds through local wadi floods	<50-150	8.64	Consolidated and unconsolidated sediments.	Inter-granular and Fracture	-0.138	3
9	Flood Water from the highlands	<50	-4.80	Metamorphic rocks and intrusives.	Fracture	-0.116	4
10	Recharge from wadi beds through local wadi floods	<50	12.48	Consolidated sediments, unconsolidated Sediments.	Fracture (Karst)	-0.138	0

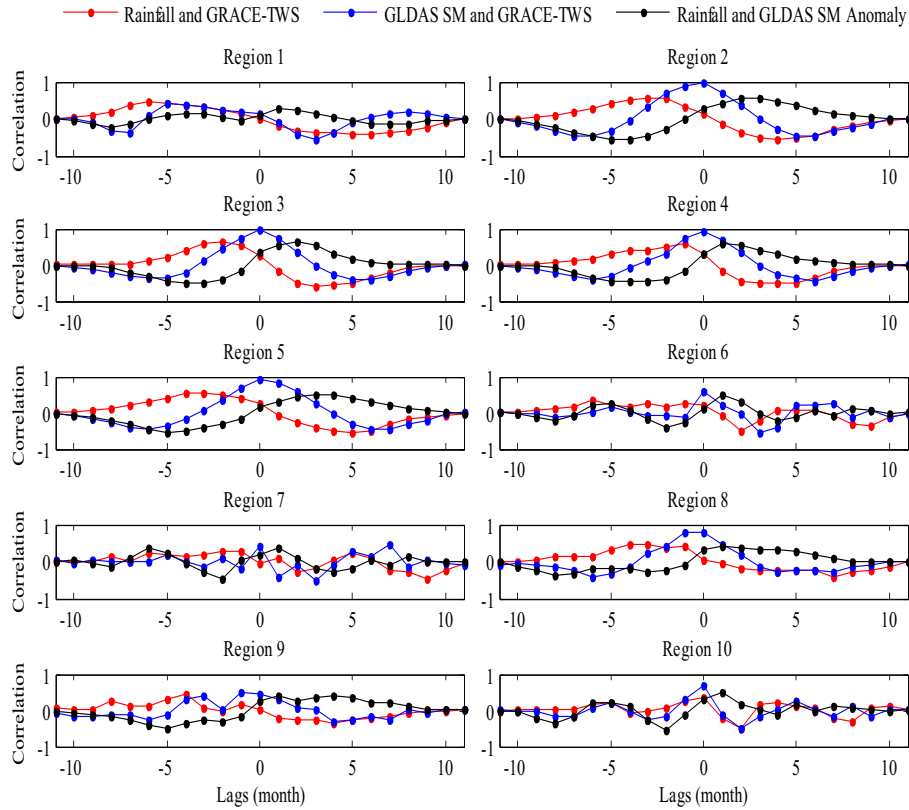


Figure 10: Correlation between different data sets (TWS, soil moisture, and rainfall) at 95% confidence level.

540 (region 4) and central (region 5), two deductions could be made, i.e., i) either
 541 the regions are source of water (e.g., regions 2, 4 and 5) or, ii) the reliance of
 542 the groundwater storage variability on the rainfall pattern is minimal.

543 5. Discussion

544 5.1. Topographic Impact on TWS

545 As one can see from the results presented in Fig. 3 (top) and Fig. 4, the
 546 influence of topography on the TWS may be inferred. From these figures, the
 547 highland dominated regions of Ethiopia, i.e., the western highlands (Fig. 2, re-
 548 gions 2, 3, 4 and 5) show greater variability in TWS than the lowland-dominated

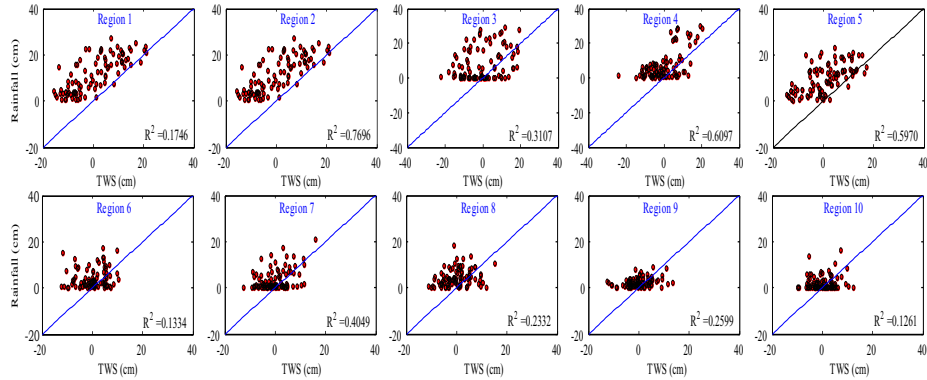


Figure 11: Relationship between TRMM rainfall in January and GRACE TWS in July for each region at a lag of six months. This lag is chosen as an example to show the impact of the January rainfall on TWS in July.

549 regions. In addition, from the lag correlation presented in Fig. 10, one can see
 550 the influence of the regime’s hydrogeology on its response to rainfall. For in-
 551 stance, the karst dominated regions (i.e., 10 in Table 2) has zero lag while the
 552 unconsolidated sediment dominated region 1 has a lag of around 6 months.

553 However, hydrological fluxes are expected to differ greatly from the outlet to
 554 high elevations for some of the areas in the Ethiopian highlands. Whereas pre-
 555 cipitation is expected to increase with elevation (depending on aspect), poten-
 556 tial evapotranspiration decreases with elevation due to reduced temperatures at
 557 higher elevations (cf., [Berhanu et al., 2013](#)). Based on water balance estimates,
 558 runoff is therefore expected to be greater at higher elevation than lower ones for
 559 high gradient basins facing the prevailing storm movement direction. The total
 560 amount of runoff from the basin will therefore depend on the hypsometric re-
 561 lationship, i.e., the relative proportions of drainage area at different elevations.
 562 Since evapotranspiration will vary with the type of vegetation, changes in land
 563 use will also have a potential impact on the amount and type of evaporation
 564 (from either surface or groundwater sources). In addition, the conversion of
 565 relatively undisturbed (e.g., forested) areas to more intensive agriculture will
 566 greatly increase surface runoff at the expense of groundwater recharge due to

567 reduced infiltration capacity. We therefore believe it is critical to assess the role
568 of elevation in hydrological fluxes coupled with seasonal variability and changes
569 under potential climate scenarios.

570 *5.2. Possible Human Influence on the Observed TWS*

571 Ethiopia is a highly populated region that has seen a number of dams con-
572 structed and high levels of water withdrawal from groundwater and surface water
573 reservoirs, which would impact upon the total water storage (e.g., [Berhane et al.,](#)
574 [2013](#); [Tesfagiorgis et al., 2011](#)). Large scale land-use and land-cover changes in
575 Ethiopia due to agricultural expansion and heavy grazing have been reported
576 (e.g., [Descheemaeker et al., 2009](#); [Bewket & Abebe, 2013](#)). In addition, [Hurni](#)
577 [\(1988\)](#) and [Nyssen et al. \(2004\)](#) have reported that land degradation is a serious
578 problem to Ethiopia. Ethiopia is an agrarian country, where more than 85%
579 of its population depend on irrigated agriculture, with production in certain
580 regions being highly dependent on the available water resources (i.e., surface
581 water and groundwater). The total area under irrigation in Ethiopia is about
582 of 290,729 ha ($\sim 0.3\%$ of the country's area), with about 2,611 ha depending on
583 groundwater irrigation ([Siebert et al., 2013](#)). The irrigation water demand in
584 Ethiopia is estimated to be $40 \text{ km}^3/\text{year}$ ([Egziabher, 2000](#)), with an estimated
585 $2.6\text{-}6.5 \text{ km}^3/\text{year}$ of groundwater potential ([Awulachew et al., 2007](#)). The prin-
586 cipal grain crops are wheat, barley (primarily cool-weather crops) and corn,
587 sorghum, and millet (warm weather grain crops).

588 Since the GRACE products can resolve large areas to the tune of hundreds of
589 km (i.e., $450 \text{ km} \times 450 \text{ km}$), the impact of anthropogenic activities at hill slope
590 scales, such as those discussed in [Descheemaeker et al. \(2009\)](#), on its signals will
591 not be detectable. However, if such impacts occur over a wider scale that is of
592 the same order as the resolution of GRACE, then they may be detectable.

593 TSD in percent (Eq. (4)) are computed from the GRACE-derived TWS
594 anomalies and presented in Fig. 12. Depending upon their TSD patterns,
595 Ethiopia can be divided into three different zones. In the first zone, we have
596 regions 2, 3, 4, and 5, while regions 1 and 6 are in zone 2, with regions 7, 8, 9 and

597 10 in the third zone. For the three zones, TSD decreased from the beginning
598 of 2003 until around mid-2006 for zones one and two, and January 2005 for the
599 third zone. Then, for the first and third zones, it started to rise in 2006, while
600 for the second group this was from around the beginning of 2007. The decrease
601 in TSD starting from Jan-2003 indicates increasing dryness, which may be due
602 to the propagation of the 2002 drought in Ethiopia ([Anderson & Choularton,
603 2004](#)). In regions where significant TSD has been seen from 2003 to 2006 (e.g.,
604 Zone 1 in Fig. 12), the main crops are teff, sorghum, maize, wheat and millet.
605 Despite the decrease in TSD in the regions, there has been an increase in crop
606 production area and yield ([Eberhardt, 2008](#)), indicating on the one hand that
607 such crops can be sustained under such water deficit conditions. However, on
608 the other hand, this could indicate that the greater portion of this deficit in
609 TWS could be due to groundwater storage depletion. This, however, remains
610 an open question for future investigations.

611 In regions 1, 2, 3, and 9, over the study period, very significant water loss
612 was identified (see Fig. 5, bottom), especially when compared to the recharge
613 amount per year, as stated in Table 2. This might be attributed in part to
614 human exploitation and partly due to climate impacts discussed below.

615 From the developed TDC using 96 months of GRACE derived TWS data
616 (Fig. 6), the lower end of the curve might be due to extreme water depletion
617 cases, while the upper end results from high rainfall condition with long re-
618 turn periods. This is again an open question subject to future investigations.
619 Nonetheless, to see the real variation of TWS, the slope of the TDC in the
620 region where one can assume linearity is computed. If this slope is expressed
621 in percentage, it varies between -14% to -35%. There are several factors that
622 might affect the slope of the TDC, e.g., soil moisture, hydrogeological setting,
623 aquifer flow, storage types, storage potential, recharge rates and recharge mech-
624 anisms. With the characteristics listed in Table 2, and their TDC slope, one
625 notes that (i) region 2 has the smallest storage potential compared to the oth-
626 ers, (ii) regions 3, 4 and 5 have intermediate storage potentials, and (iii) all the
627 other regions have relatively large storage potentials. From Fig. 11, although

628 most regions have correlation coefficients of less than 0.5, Fig. 4 on the other
 629 hand show that certain regions gained TWS. This could indicate that a certain
 630 proportion of the TWS in the regions is contributed by subsurface inter flow
 and dominant indirect recharges.

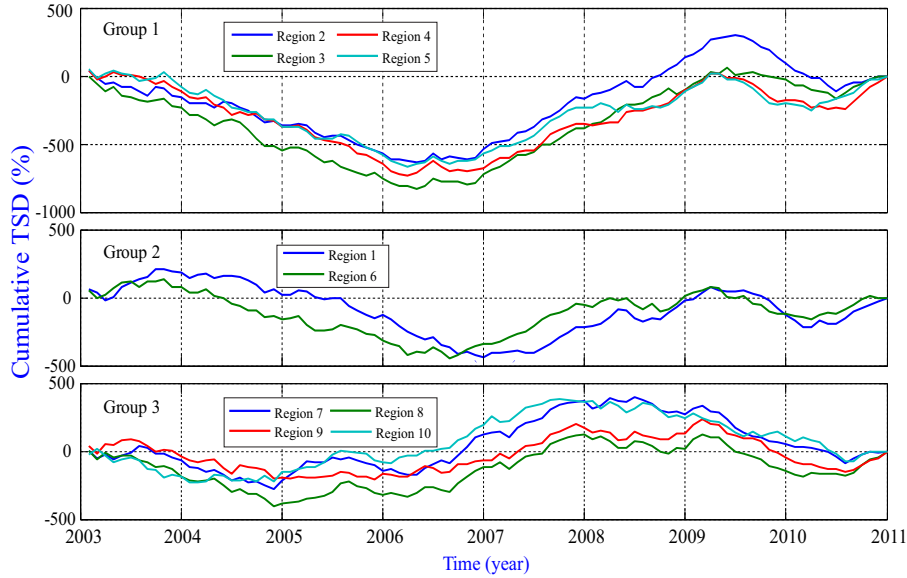


Figure 12: Total Storage Deficit (TSD) derived for the main 10 regions defined over Ethiopia subdivided into different zones. The values are in percent (see Eq. (4)).

631

632 5.3. Climate Impact on the Observed TWS

633 The extreme depletion in TWS and GW in certain regions during February
 634 2003 (see PC1 of TWS in Fig. 4) could probably be due to the reported droughts
 635 in the year 2002 (Anderson & Choularton, 2004). This is further supported when
 636 they are considered together with the lag determined from TWS and rainfall
 637 correlation (Fig. 10). Rainfall over Ethiopia is known to be seasonal, having dry
 638 and rainy seasons (Seleshi & Zanke, 2004). The effect of this seasonality seems
 639 to be reflected in the TWS anomalies, having two distinct seasons on average,
 640 the water lose (winter, 21.3 mm/month and spring, 36.6 mm/month) and water
 641 gain (summer, 14.4 mm/month and autumn, 41.0 mm/month) seasons. PCA

642 results showed that the annual peaks of rainfall are also very important and are
643 highly correlated to the annual peaks of TWS, thus indicating that rainfall is
644 the main driving factor for the rise in TWS levels in most parts of Ethiopia.
645 Although climatic factors such as drought could be a contributor towards the
646 fall in TWS levels, as pointed out earlier, human influences may also contribute.

647 The dominant hydrogeologic regimes, recharge mechanisms, recharge rates,
648 aquifer flow and storage types for each region are presented, e.g., in [Chernet](#)
649 [\(1993\)](#) and [Abiye \(2010\)](#). Here we discuss the results obtained in relation to the
650 properties of the regions described in the [Table 2](#). The aquifers response lags to
651 rainfall computed in this study are also listed in [Table 2](#). For the same aquifer
652 flow and storage type, one can notice that there are different lag values, see,
653 e.g., regions 2 and 3 in [Table 2](#), which could be attributed to the nature of the
654 recharge mechanism in each region. Furthermore, regions that are dominated
655 by the inter-granular aquifer flow and storage type are seen to have a longer lag
656 periods (regions 1, and 6), while karst dominated regions show a direct response
657 to rainfall (region 10).

658 In the north-west (region 3) a lag of 2 months is noted ([Table 2](#)). This
659 shows that it takes 2 months from when it rains to the time when the impact on
660 TWS is visible, hence making the transfer of water from one season to another
661 impossible. This implies that for most parts of Ethiopia, the rainfall in the
662 previous season might have an impact on the TWS of the current season at
663 most, but cannot have an effect later further. In regions 2, 5 and 8, the cross
664 correlation between rainfall with TWS indicated a lag of 3 months ([Table 2](#)).
665 [Figure 11](#) also shows that there is a high correlation between rainfall and TWS
666 in regions 2 and 5, indicating that the influence of rainfall on TWS in these
667 regions is higher than subsurface inflow from adjacent regions. TWS in region
668 9 recorded a lag of 4 months from the rainfall ([Table 2](#)), although this region
669 has low rainfall and also displays a poor correlation between rainfall and TWS
670 anomaly ([Fig. 11](#)).

671 The mean annual rainfall for regions 1 and 6 have two small peaks, with
672 a lag of 6 months obtained from the TWS/Rainfall cross correlation, implying

673 that the autumn water gain is mainly from the rainfall received in winter. With
674 the characteristics described in Table 2, these regions have the property of being
675 able to transfer water mass gained from rainfall in a certain year to the next
676 one. According to Kebede (2013), 3/4 of Ethiopia's aquifers receive localized
677 and indirect recharge. This implies that only 1/4 of Ethiopia's aquifers should
678 exhibit a good correlation between TWS and rainfall. The R^2 results obtained
679 from correlation analysis in Fig. 11 supports this assertion.

680 In the northern (region 4) and south eastern (region 7) regions, a lag of
681 one month between TWS and rainfall was obtained from the cross correlation,
682 implying that the aquifer responds to the rainfall after about one month. From
683 the slopes of the TDC, region 4 has a lower storage potential than region 7,
684 while the rainfall in region 4 is a bit higher than in region 7. One may therefore
685 conclude that the chance that water can be transferred from a rainy to non-
686 rainy season in such regions is very low. In this case, the rise or fall in TWS in
687 certain season is mostly subject to the rainfall for that particular season.

688 6. Conclusions

689 Time series of terrestrial water storage anomalies (TWS), soil moisture, and
690 rainfall over Ethiopia were derived from GRACE, GLDAS, and TRMM data sets
691 and products, respectively, and analyzed with the aim of better understanding
692 the relationship between rainfall and groundwater variations over Ethiopia's
693 aquifers. The inter-annual and seasonal variability of water storage, the rela-
694 tionship between water storage changes with rainfall and soil moisture, and the
695 aquifers' characteristics and TWS anomalies have been derived over a period of
696 8 years from 2003 to 2011. The study indicates that the western part and the
697 north-eastern lowland of Ethiopia are losing water. From seasonal analysis, the
698 seasons when water is gained are found to be summer and autumn, while the
699 loss seasons are spring and winter for most parts of Ethiopia. Soil moisture and
700 rainfall variations showed the dominant annual water variability in the western,
701 north western, northern and central regions, and the dominant seasonal vari-

702 ability in the western and eastern regions. Change in soil moisture was seen to
703 have less influence over the total water storage, while groundwater storage has
704 a dominant influence. From a correlation analysis between TWS and rainfall,
705 lags of 2 to 3 months for most regions were observed, indicating the capacity
706 of a large portion of the Ethiopian groundwater storage (aquifers) to transfer
707 water mass gained in certain periods to be less than 3 months. If validated at
708 a finer spatial resolution, this could be vital information for water managers
709 to know, that if an increase in TWS is required to back up water availability
710 in dry seasons, one has to focus on increasing soil moisture and surface water
711 storage rather than groundwater storages. The information could also be vital
712 in land-use planning issues.

713 **Acknowledgment**

714 G. Wakbulcho thanks the United States Agency for International Devel-
715 opment (USAID) for the financial support during the period of undertaking
716 this research. He is further grateful to Arba Minch University (Ethiopia) for
717 supporting his stay at EIWR. The authors thank the providers of GRACE-
718 GFZ, GLDAS and TRMM data used in this study. The authors are grateful
719 to the Editor Prof Gabriel Katul and the three reviewers (Dr. Kevin Fleming
720 and two anonymous reviewers) for their valuable comments that enriched the
721 manuscript. This is a TIGeR publication No. 575.

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