Hydrological controls on surface vegetation dynamics over West and Central Africa

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Abstract

A considerable number of independent case studies have shown the explicit role of rainfall and soil moisture as drivers of surface vegetation dynamics. However, the weak relationship exhibited by rainfall and soil moisture with vegetation productivity in some semi-arid and humid ecosystems of Africa due to a complex combination of social and environmental factors warrants further assessment of hydrological controls on surface vegetation changes. In this study, hydrological control on surface vegetation in West and Central Africa (WCA) using monthly Normalized Difference Vegetation Index (NDVI) (2002 – 2013) as a vegetation proxy, is explored by using terrestrial water storage (TWS) inverted from time-variable satellite gravity observations. Statistical relationships indicated that the temporal patterns of NDVI with TWS over West Africa, and in catchment-specific cases, were generally slightly stronger than the widely reported association between rainfall and NDVI. The strongest temporal association between TWS and NDVI was found in Lake Chad basin ($R^2 = 69\%$ at $\alpha = 0.05$) and southern Mali ($R^2 = 62\%$ at $\alpha = 0.05$). However, when the spatial relations of TWS-NDVI and rainfall-NDVI were evaluated (monthly and seasonal scales), rainfall showed a considerable and wider spread of significant association ($\alpha = 0.05$) with surface vegetation greenness compared to TWS. But some locations in the semi-arid Sahel exist where spatial relationships between NDVI and TWS were relatively higher and consistent as opposed to the rainfall-NDVI relationship. A contemporary understanding of the water driven variability in surface vegetation in WCA indicates that (i) the preponderance of observed positive correlations of NDVI with TWS and rainfall are predominantly found in the Sudano-Sahelian ecosystems, where total NDVI variability is apparently the highest (51.4%) and (ii) some of the Sahelian vegetation also show considerable and significant association with model-derived groundwater. As a strong hydrological indicator in rain-fed semi-arid catchments of West Africa, TWS can be

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employed as a resourceful tool to provide early warning systems and improve the monitoring of climate impacts on groundwater dependent vegetation communities.

9 *Keywords:* NDVI, Sahel, Water, Rainfall, Groundwater, Climate variability

10 **1. Introduction**

11 Mankind depends on healthy vegetation for the provision of energy, food, and other essen-
12 tial services such as regulating the climate system, storing carbon, and hosting biodiversity
13 (e.g., [Trumbore et al., 2015](#), [Zeng et al., 1999](#)). The need to assess the response of surface vege-
14 tation to changes in hydrological conditions is therefore crucial. To highlight the constraints of
15 water on terrestrial ecosystems and regional land surface phenology, soil moisture and rainfall
16 products are commonly used (see, e.g., [Guan et al., 2014](#), [Knauer et al., 2014](#), [Chen et al.,](#)
17 [2014](#), [Zhou et al., 2014](#), [Seghieri et al., 2012](#), [Huber et al., 2011](#), [Do et al., 2005](#), [Nicholson](#)
18 [et al., 1990](#)). Some reports however, have argued that rainfall only provides an indirect obser-
19 vation of water availability (e.g., [Chen et al., 2014](#), [Yang et al., 2014](#)). The uncertainties that
20 characterize regional precipitation estimates and water budget indicators are key challenges
21 in understanding vegetation response to water constraints (e.g., [A et al., 2015](#), [Zhang et al.,](#)
22 [2009](#)).

23 Globally, the impacts of climate change on ecosystem productivity may trigger complex
24 terrestrial ecosystem response to hydrological conditions. In southwestern North America, for
25 example, surface vegetation greenness is both a function of dry season length and precipitation
26 with the former playing a more significant role in vegetation growth ([Zhang et al., 2010](#)). The
27 length of rainy season in some African regions does have strong non-linear impacts on tree
28 fractional cover due to compound mechanisms of hydrological cycle ([Guan et al., 2014](#)). But
29 in dry tropical areas, a decrease in temperature was found to be the strongest predictor of
30 both leafing and reproductive phenophases in the Sahel ([Seghieri et al., 2012](#)).

31 Region-specific case studies in West Africa (Fig. 1a) as summarised in [Knauer et al. \(2014\)](#)
32 agree that it is somewhat difficult to satisfactorily untangle the impact of precipitation on its
33 vegetation system due to a number of factors that include, e.g., extreme rainfall variability,
34 complex landscapes and hydrological processes. Although rainfall appears to be the leading
35 determinant of understanding vegetation distribution in much of the West African Sahel, the
36 weak relationship between rainfall and NDVI in wetland areas (e.g., [Georganos et al., 2017](#))
37 suggests the role of other drivers, and underpins the need for ideal indicators. While the
38 evolving rainfall-NDVI relationship in some regions of West and Central Africa (WCA) may

39 be complex, accumulating evidence from considerable case studies as compiled by [Knauer et al.](#)
40 (2014) confirm that rainfall has not sufficiently explained changes in surface vegetation green-
41 ness in West Africa. This has been attributed mostly to human influence and the impacts of
42 climate change (see, e.g., [Dardel et al., 2014](#), [Jamali et al., 2014](#), [Knauer et al., 2014](#), [Boschetti](#)
43 [et al., 2013](#), [Olsson et al., 2005](#), [Herrmann et al., 2005](#), [Li et al., 2004](#)). Further, whereas model-
44 derived soil moisture is rather poorly associated with vegetation dynamics in the African Sahel
45 (e.g., [Huber et al., 2011](#), [Do et al., 2005](#)), the complex formation of the African rainforest lim-
46 its satellite moisture observations in the study of vegetation water dynamics. As mentioned
47 in [Dirmeyer et al. \(2004\)](#), soil moisture observations from remote sensing platforms may be
48 limited and largely restricted in highly dense vegetation community, as plant tissues, which
49 contain significant amount of water weaken the intensity of the microwave signal.

50 The morphological and physiological adaptations of Sahelian vegetation results in complex
51 water use mechanisms during the dry season (e.g., [Guan et al., 2014](#), [Seghieri et al., 2012](#),
52 [Huber et al., 2011](#)) and may further restrict soil moisture as a useful indicator for vegetation
53 dynamics. Although it is arguably the most suitable indicator in understanding land surface
54 phenology and the response of plants to the changing climate system (see, e.g., [Chen et al.,](#)
55 [2014](#), [Huber et al., 2011](#)), satellite soil moisture observations may be restricted in landscapes
56 where vegetation and plant cover, overwhelmingly depend on soil water from the saturated
57 zone. This limitation, inter alia, can be attributed to large retrieval errors (e.g., [Högstrom](#)
58 [et al., 2014](#)) and the fact that satellite soil moisture observations are mostly restricted to the
59 few centimeters of the top soil (e.g., [Yang et al., 2014](#)). The root depth of most Sahelian
60 vegetation, for instance, extends to the water table region, which lies up to 40 m below the
61 surface during the dry season ([Huber et al., 2011](#), [Do et al., 2005](#)). This makes some of the
62 Sahelian trees much less sensitive not only to inter-annual changes in rainfall but also to changes
63 in soil moisture (be it satellite or model-derived). In addition, environmental, pedological
64 (e.g., soil characteristics), and hydro-climatological conditions amongst other factors contribute
65 considerably to the diversity in local hydrology, creating uncertainties in our knowledge of
66 vegetation response to land surface conditions (e.g., soil wetness). Under these conditions,
67 both soil moisture and precipitation may be largely restricted as hydrological controls for
68 vegetation dynamics in the African Sahel.

69 Consequently, terrestrial water storage (TWS; total of soil moisture, groundwater, surface
70 water, wetlands, canopy, etc.) derived from satellite gravity observations such as the Gravity
71 Recovery and Climate Experiment (GRACE, [Tapley et al., 2004](#)) is introduced to further en-

hance our understanding of the non-linear and spatially heterogeneous relationships between surface vegetation and hydrological indicators in WCA. GRACE observations are emerging as an alternative product to (i) evaluate temporal and spatial dynamics in soil moisture and groundwater at watershed scale, and to assess the productivity of agro-ecological system of a semi-arid catchment (e.g., [Ndehedehe et al., 2018a](#), [Abiy and Melesse., 2017](#), [Famiglietti, 2014](#), [Wouters et al., 2014](#)) (ii) study the impact of climate variability on vegetation water changes in arid ecosystems and Arctic biomes (see, [A et al., 2015](#), [Yang et al., 2014](#)), and (iii) assess hydrological processes, water budget, drought variability, sub-surface water storage, and aquifer system processes (e.g., [Ferreira et al., 2018](#), [Ndehedehe et al., 2016a, 2017a](#), [Ferreira and Asiah, 2015](#)). However, its use in the data deficient WCA as a proxy for available plant/vegetation water, has not been reported. Because of the restrictions of soil moisture in water-limited ecosystems as drivers of vegetation dynamics, and the fact that sub-surface water use during dry season exists in the Sahel region (see, e.g., [Guan et al., 2014](#), [Huber et al., 2011](#)), investigating the potential use of GRACE-derived TWS as a driver of vegetation dynamics is essential. This study is critical and provides complementary perspectives on water availability as a driver of vegetation dynamics. Whereas it further advances our knowledge of African ecology and its biophysical systems, this study extends GRACE-derived TWS as an innovative biophysical tool that could support global terrestrial ecosystem assessment, especially in data sparse regions.

The main objective of this study is to investigate the potential of GRACE-derived TWS (hereafter TWS) as a hydrological control for observed changes in surface vegetation over West and Central Africa based on temporal and spatial relationships. Here, surface vegetation is characterised by monthly time series of Normalized Difference Vegetation Index (NDVI). More specifically, the study aims to (i) assess the temporal relationships of NDVI with TWS and rainfall, (ii) investigate the leading independent spatio-temporal patterns of NDVI over WCA, and (iii) assess the spatial relations of NDVI with TWS, rainfall, and groundwater at monthly and seasonal time scales. The WaterGap groundwater model data ([Döll et al., 2014](#)) used in this study is included to help assess regions whose vegetation systems may be groundwater-dependent.

Figure 1: Study area showing countries and other sub-regions in West and Central Africa (this current study focuses on all countries in West Africa and some regions of Central Africa or the Congo basin and are otherwise or collectively known as West and Central Africa (WCA) for convenience). (a) Location map showing countries of West Africa, Equatorial region/Congo basin, and hydrological units, (b) land cover map extracted from the Moderate Resolution Imaging Spectroradiometer-MODIS (MCD12Q1) Land Cover products (the data can be accessed using the spatial data access tool available at http://webmap.ornl.gov/ogcdown/dataset.jsp?ds_id=10004), (c) the annual rainfall, and (d) mean annual NDVI during the 2003 – 2013 period averaged over WCA. Note that (a) and (b) above have been slightly modified from Ndehedehe et al. (2018c).

2. The vegetation system of West and Central Africa and response to climate

The coastal regions of West and Central Africa (WCA) and with several hydrological networks (Fig. 1a) are heavily forested ecosystems (Fig. 1b) with considerable amounts of annual rainfall (Fig. 1c) compared to the semi-arid and arid ecosystems found in Sudano and Central Sahel belt, respectively. Surface vegetation dynamics in West Africa is largely sensitive to water availability, which is largely modulated by climate variability. The seasonal distribution of NDVI in the region, for example, predominantly follows the climatic zones, with

vegetation density decreasing gradually from the humid tropical rainforest of the Guinea Coast and Equatorial countries through the semi-arid Sahel region to the Sahara Desert (Fig. 1b and d). This diversity in ecosystem and species richness and vegetation density (Figs. 1b and d) in the region is largely driven by the migration of the tropical rainbelt, leading to over 2500 mm/yr of annual rainfall in the Guinea Coast and Equatorial countries (hereafter called coastal countries) and less than 500 mm/yr in the Sahelian countries (Fig. 1c). Specifically, in the Central African Republic (CAR, see Fig. 1d) where several vegetation formations ranging from savannas, swamp forests, to other forests are found to be strongly correlated with rainfall (Gond et al., 2013). High NDVI values in almost all seasons except the period between September and December are predominant (Fig. 1d). Similarly, NDVI values are relatively high (about 0.8) and decreases (between 0.6 and 0.7) towards the end of the year in the upland Congo basin where a considerable amount of evergreen broadleaf forests are mostly embedded in swamps (Figs. 1b and d). In this study, the response of NDVI to TWS and rainfall is analysed with respect to dominant plant covers (Fig. 1b) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover products.

3. Data

3.1. Normalised Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is sensitive to vegetation condition and is associated with vegetation primary production and photosynthetically active radiation (e.g., Tucker et al., 2005, Herrmann et al., 2005). Several studies have used it to monitor changes in surface vegetation and water stress in plants (e.g., Dardel et al., 2014, Chen et al., 2014, Jamali et al., 2014, Knauer et al., 2014, Boschetti et al., 2013, Olsson et al., 2005, Herrmann et al., 2005, Nicholson et al., 1990). The monthly NDVI data used in this study is an 8 km spatial resolution data prepared by the Global Inventory Modelling and Mapping Studies (GIMMS) (e.g., Tucker et al., 2005, Herrmann et al., 2005) and is available for download (<http://ecocast.arc.nasa.gov/data/pub/gimms/>). This archived NDVI data was already corrected for cloud cover, atmospheric water vapour, and residual sensor degradation and is suitable for vegetation studies (see, e.g., Herrmann et al., 2005, Tucker et al., 2005). The consistency of the GIMMS NDVI product with three other NDVI datasets (based on the Advanced Very High Resolution Radiometer), field measurements, and MODIS-derived NDVI has already been assessed (Dardel et al., 2014). The NDVI product (GIMMS-3g) used to

analyse the variability in surface vegetation greenness over WCA are the monthly maximum composites and covers the period of 2002 – 2013. The annual NDVI time series were derived by aggregating these monthly maximum composites over WCA. In order to maintain a common spatial resolution with TWS (Section 3.2) before applying the spatial correlation, NDVI was re-projected and aggregated to a $1^\circ \times 1^\circ$ grid.

3.2. GRACE-derived terrestrial water storage (TWS)

Gravity Recovery and Climate Experiment (GRACE, Tapley et al., 2004) satellite mission provides an integrated sum of changes in surface waters, catchment stores (e.g., groundwater, soil moisture, etc.), and canopy based on the observations of the Earth’s time variable gravity field. GRACE observations have been extensively used to study the Earth’s water storage changes and hydro-meteorological conditions at regional, continental, and global scales (e.g., Agutu et al., 2017, Van Loon et al., 2017, Ndehedehe et al., 2016b, Swenson and Wahr, 2007, Wouters et al., 2014). In this study, the GRACE Release-05 (RL05) spherical harmonic coefficients obtained from Center for Space Research (CSR) (see, <http://icgem.gfz-potsdam.de/ICGEM/shms/monthly/csr-rl05/>) covering the period of 2002 – 2014, are used to estimate terrestrial water storage (TWS) over the region on a $1^\circ \times 1^\circ$ grid following the approach of Wahr et al. (1998) as

$$\Delta TWS(\phi, \lambda, t) = \frac{R\rho_{ave}}{3\rho_w} \sum_{l=0}^{l_{max}} \frac{2l+1}{1+k_l} \sum_{m=-l}^l P_{lm}(\phi, \lambda) \Delta Y_{lm}(t), \quad (1)$$

where ΔTWS is the equivalent water height (hereafter TWS) for each month in time (t), and where ϕ and λ are the latitudes and longitudes, respectively. R is the mean radius of the Earth (i.e., 6378 km), ρ_{ave} is the average density of the Earth (5515 kg/m^3), ρ_w is the average density of water (1000 kg/m^3), k_l is the load Love numbers of degree l , P_{lm} are the normalized spherical harmonic functions of degree l and order m with $l_{max}=60$ and ΔY_{lm} are the normalized complex spherical harmonic coefficients after subtracting the long term mean. Other processing details follow approaches fully described in previous studies (e.g., Landerer and Swenson, 2012) and are only briefly summarised here. Region-specific estimates of TWS values (W) were computed using the area weighted average

$$\Delta W(\chi; t) = \sum_{i=1}^n \Delta TWS(\phi_i, \lambda_i, t) \frac{A_i}{A_\chi}, \quad (2)$$

where χ is the basin index, n is the number of pixels in the basin, A_i is the area of the grid cell i in χ and A_χ is the total area of χ . Note that GRACE-derived TWS is simply referred to as TWS in the manuscript for convenience.

3.3. *WaterGap global hydrology model (WGHM)*

The global hydrological model WaterGAP (Döll et al., 2014) is used to derive groundwater component over WCA for the period 2002 – 2009. This model takes into account groundwater recharge from surface water bodies in semi-arid and arid regions and groundwater depletion. Specifically, it combines monthly net abstractions from groundwater and surface water together with climate and physiogeographic data as inputs while its outputs were compared to several independent regional-scale estimates of groundwater recharge and abstractions (Döll et al., 2014). The relationship between groundwater and NDVI is examined using correlation analysis during the common period for which the groundwater model data is available. The WaterGAP model (version 2.2a) data used in this study has a spatial resolution of $0.5^\circ \times 0.5^\circ$ and was downloaded from Center for Environment Systems Research website.

3.4. *Precipitation from tropical rainfall measuring mission*

Tropical Rainfall Measuring Mission (TRMM 3B43) (Kummerow et al., 2000) based precipitation, covering the period 2002 – 2013 is used in this study to examine vegetation response to rainfall variability. The data has a global coverage between 50°S and 50°N with a spatial resolution of $0.25^\circ \times 0.25^\circ$. Monthly TRMM precipitation were resampled to a $1^\circ \times 1^\circ$ grid before applying the spatial correlation in order to maintain a common spatial resolution with other datasets such as the NDVI and TWS solutions. The data is available at the National Aerospace and Space Administration (NASA) Goddard Space Flight Center (GSFC) website (<http://disc.gsfc.nasa.gov/datacollection/TRMM3B43-V7.shtml>).

4. Methods

4.1. *Multivariate analyses*

The Independent component analysis (ICA, e.g., Cardoso and Souloumiac, 1993, Common, 1994, Cardoso, 1999) was employed to examine the spatial variability and temporal characteristics of NDVI in relation to those of TWS and rainfall during the common period (2002 – 2013). This cumulant based statistics decomposes monthly grids of NDVI into spatial and temporal

194 patterns as

$$\mathbf{X}_{NDVI} = \mathbf{B}\mathbf{E}^T, \quad (3)$$

195 where $\mathbf{X}$ is the NDVI data matrix with rows and columns representing months and the NDVI
 196 grid values over West and Central Africa (WCA), respectively. $\mathbf{B}$ contains the independent
 197 components (ICs) (also known as the NDVI temporal evolutions), which are scaled by its
 198 standard deviation and $\mathbf{E}^T$ the NDVI spatial patterns, which are scaled by multiplying with
 199 the standard deviation of its corresponding ICs. Regionalising NDVI using ICA techniques
 200 offers the opportunity to understand space-time evolutions and dominant modes of surface
 201 vegetation dynamics in the region. The relationships of four leading temporal modes of NDVI
 202 regionalize over WCA with standardised anomalies of TWS and rainfall averaged over West
 203 Africa, the Sahel region, and the Congo basin area were further examined using correlation
 204 and regression analyses. Further details about the application of this method can be found in
 205 previous studies (e.g., [Ndehedehe et al., 2016b,c](#), [Frappart et al., 2011](#)). Based on multi-linear
 206 regression analysis (MLRA) framework, the residual variability of NDVI was compared to
 207 those of TWS and rainfall through parameterizations of their trends and harmonic components
 208 (mean annual and semi annual amplitudes), as (e.g., [Ndehedehe et al., 2017b](#))

$$\mathbf{y}_t(x, y) = \beta_0 + \beta_1 t + \beta_2 \sin(2\pi t) + \beta_3 \cos(2\pi t) + \beta_4 \sin(4\pi t) + \beta_5 \cos(4\pi t) + \varepsilon(t), \quad (4)$$

209 where $\mathbf{y}$, is the data (NDVI, TWS, rainfall), (x, y) are grid locations, t is the time, β_0 is the
 210 constant offset, β_1 is the linear trend, β_2 and β_3 accounts for the annual signal while β_4 and
 211 β_5 represents the semi-annual signal, and $\varepsilon(t)$ is the random error term. After removing the
 212 trends and the harmonic components (i.e., $[(\beta_2)^2 + (\beta_3)^2]^{1/2}$ and $[(\beta_4)^2 + (\beta_5)^2]^{1/2}$) for the
 213 annual and semi annual amplitudes, respectively) of the NDVI data, the residual part was
 214 compared with those of TWS and rainfall. This is done to examine which of TWS and rainfall
 215 reflects better the internal variabilities in NDVI.

216 4.2. Correlation analyses, trends, and cumulative departures

217 The temporal and spatial relationships of NDVI with TWS, rainfall, and groundwater were
 218 examined using Pearson's correlation coefficients (r). The grid by grid (spatial) comparison
 219 was achieved by re-projecting and aggregating NDVI and precipitation to a $1^\circ \times 1^\circ$ spatial res-
 220 olution as TWS prior to correlation. The cross-correlation method was used to determine the
 221 time lag in the data when maximum correlation occurred. Furthermore, monthly anomalies,

and cumulative departures were estimated for TWS, NDVI and rainfall. Monthly anomalies for NDVI, TWS, and precipitation were estimated by removing the long term mean. To compute the annual cumulative departure for each data, these monthly anomalies were aggregated to yearly values. Cumulative departures of these variables are helpful as a general indicator of trends, with the upward and downward gradient indicating relatively a rise and fall, respectively. Be it monthly anomalies or cumulative departures, correlation analysis and coefficient of determination (R^2) were employed in this study to assess evolving temporal and spatial relationships of NDVI with rainfall and TWS. Furthermore, trends in NDVI, rainfall, and TWS were estimated for each grid cell using non-parametric method. Based on the least squares estimation of the regression coefficient, MLRA can also be used to estimate trends as parameterised in Eqn 4 above (Section 4.1). However, the Sen's slope (Sen, 1968) estimator was used to estimate trends since it is robust and resistant to outliers. Sen slope (S_i) is the median overall values of the whole data and is estimated as

$$S_k = \text{Median}\left(\frac{P_j - P_i}{j - i}\right), \text{ for } (1 \leq i < j \leq n), \quad (5)$$

where P_j and P_i represents data values at time j and i ($j > i$), respectively while n is the number of data. The slope can be positive indicating increasing trend or negative, indicating decreasing trend.

5. Results and discussion

5.1. GRACE-derived TWS hydrological control on the temporal variations of NDVI

In this Section, the results of temporal variations, seasonal, and mean annual cycles of Normalized Difference Vegetation Index (NDVI) are compared with those of terrestrial water storage (TWS) and rainfall. Specifically, the potential of TWS as an alternate indicator to rainfall in understanding vegetation response to hydrological conditions along different climatic belts in the region is discussed. Although the scope of this work is limited to countries in West and Central Africa, it should be noted that the statistical relationships developed between NDVI and TWS/rainfall would be similar to and rather typical of other tropical and semi-arid or arid ecosystems in the world.

5.1.1. Temporal patterns of mean annual cycles of NDVI, TWS, and rainfall

Comparing the cumulative annual departures (i.e., cumulative annual anomalies) of NDVI with TWS and rainfall masked over West Africa, the temporal patterns of NDVI are somewhat

Figure 2: Comparison of cumulative annual departures of NDVI with those of TWS and TRMM based precipitation during the 2003 – 2013 period in WCA. (a)-(b) Cumulative annual departures (NDVI vs TWS and NDVI vs TRMM) over West Africa, (c)-(e) cumulative annual departures of NDVI with TWS, and (f)-(h) cumulative annual departures of NDVI with precipitation over the selected basins/catchments (southern Mali, Lake Chad and Congo basins).

251 consistent with those of rainfall, both indicating a fall during the 2003 – 2005 period (Fig. 2a-
 252 b). NDVI showed a rise during the 2005 – 2013 period in their cumulative annual anomalies
 253 while the increase in TWS (2009 – 2013) only came after a steady condition (turning point)
 254 during the 2007 – 2009 period (Fig. 2a). The cumulative annual departure of TWS between
 255 2007 and 2009 could be an hibernation period when the hydrology of the region was trying to
 256 reset owing to an improved rainfall condition (Fig. 2b). Unlike TWS, the cumulative departure
 257 of rainfall in Fig. 2b is characterised by several major turning points with rainfall plummeting
 258 in 2010. It seems that rainfall appears to follow the temporal pattern of NDVI except for
 259 the anomalous years of 2009 and 2011 (Fig. 2b). Furthermore, the averaged annual time

series of cumulative annual anomalies (NDVI, TWS, rainfall) in selected catchment and river basins (south Mali, Lake Chad basin, and Congo basin) were also evaluated since cumulative annual anomalies over West Africa may be dominated by the tropical regions having very large NDVI, rainfall, and TWS values. The correlation results (Table 1) for these region-specific cases suggest that the temporal dynamics in surface vegetation greenness are more associated with TWS than rainfall (Figs. 2c-h). While the annual time series of rainfall and TWS in southern Mali show significant relationships with NDVI, rainfall over the Lake Chad and Congo basins show no statistically significant association with NDVI (Table 1). But the annual cumulative departures of NDVI and TWS in the Congo basin and West Africa showed considerable and modest associations, respectively (Table 1).

The observed cumulative annual departures in Fig. 2 provide an overview of the hydrological narrative of WCA during the 2003 – 2013 period. In particular, the role of land use change on surface runoff (e.g., Descroix et al., 2009, Favreau et al., 2009, Séguis et al., 2004) and the impact of surface water schemes on hydrological regimes (e.g., Ndehedehe et al., 2017a) in West Africa, may result in complex hydrological processes that influences the temporal relationship between NDVI and TWS. Considering that GRACE-derived TWS integrates precipitation over time, and for coastal West Africa, the most variable components would mainly be surface waters (e.g., lakes and reservoirs), and soil moisture. The strong changes in these components of GRACE-TWS along the Guinea Coast of West Africa may be inconsistent with NDVI evolutions as vegetation dynamics in the region could be largely regulated by antecedent and complex conditions. For example, significant drops in rainfall may not necessarily translate to loss of surface vegetation greenness because the impact of a dry condition may also depend on the amount of TWS present in the ecosystem prior to rainfall deficits, in addition to evapotranspiration rates and land surface conditions. This is one reason why observed spatial relationships of TWS in some coastal West African countries, while insignificant in some areas, is generally significant but considerably poor and non-linear in other locations (Section 5.2). But for other semi-arid ecosystems of West Africa, vegetation productivity is largely regulated by soil wetness conditions amongst other factors, and it is therefore likely to respond faster to severe water deficit conditions. Considering that aridity is a typical feature of the semi-arid Sahel, soil moisture and groundwater are major catchment stores that would be relatively the most variable components of TWS. Hence, the temporal association of TWS and NDVI in the Sahel is expected to be significant and strong (Table 1). Nonetheless, the NDVI-TWS temporal relationship may result in significant time lags in some watersheds due

Table 1: Temporal correlations (r) of NDVI with TRMM-based precipitation and TWS in southern Mali, Lake Chad basin, Congo basin, and West Africa during the 2002 – 2013 period. Correlation coefficients are significant at the 95% significant level using the Student t-test except for those marked with *.

S/N	Temporal correlations	Southern Mali	Lake Chad basin	Congo basin	West Africa
1	NDVI vs TRMM (monthly)	0.72	0.73	0.70	0.68
2	NDVI vs TWS (monthly)	0.79	0.83	0.09*	0.74
3	NDVI vs TRMM (annual)	0.68	0.21*	0.09*	0.16*
4	NDVI vs TWS (annual)	0.79	0.58	0.42*	0.27
5	NDVI vs TRMM (annual cumulative)	0.83	-0.18*	0.17*	-0.04*
6	NDVI vs TWS (annual cumulative)	0.93	0.79	0.71	0.50

to aquifer characteristics, the extent of inundated areas, and other human interventions (e.g., Ndehedehe et al., 2016a, 2017a). Overall, unlike rainfall, the cumulative series of TWS tend to mimic that of NDVI more closely in all cases and indicate a modest association for West Africa and considerably strong relationship in selected catchments (Figs. 2a, and c-e). As TWS can act as a buffer for water availability despite rainfall deficits, such relationship can be relied upon to evaluate the availability of water (excess water or its deficit) for vegetation growth in terrestrial ecosystems.

5.1.2. Leading temporal evolutions of NDVI variability

Within the context of assessing the temporal association of NDVI with terrestrial water storage (TWS) and rainfall, this section highlights the dominant spatio-temporal patterns of NDVI over West and Central Africa (WCA). The four leading temporal evolutions of NDVI variability (Fig. 3, right) are obtained from the regionalisation of monthly NDVI grids over WCA. These temporal series of NDVI are associated with spatial patterns (Fig. 3, left) that are distributed along different climatic domains. The first NDVI mode indicates variability in the Sudano-Sahelian band while the second NDVI mode shows a dipole pattern over the Central Sahel and Guinea Coast with an opposite phase to the Guinea Coast during the September period (Fig. 3, left). This dipole, which corresponds to an approximate phase shift of 0.5 years, is caused by the latitudinal displacement of the rainbelt, leading to inter-annual variability of rainfall towards the north and south of approximately latitude 10°N (Nicholson, 2009).

With respect to the WCA region (cf. Fig. 1a-b and d), changes in vegetation density and photosynthetic activity are found to be mostly concentrated around the Sudano-Sahel belt (IC1, Fig. 3, left) and the Central Sahel (IC2, Fig. 3, left), both accounting for approximately 51.4% and 15.1% of the total variance, respectively. The observed temporal evolutions of

Figure 3: Statistical decomposition of NDVI (2002 – 2013) over West and Central Africa using the Independent Component Analysis (ICA) technique. The temporal evolutions (right) also known as independent components (ICs) have been standardised using their standard deviations. The NDVI spatial patterns (left) are scaled using the standard deviation of the computed ICs (i.e., temporal evolutions). Averaged TWS and rainfall masked over West Africa and Central Sahel have been compared with the temporal evolutions of the first and second ICA modes of NDVI. Also, rainfall and TWS in the Congo basin area (i.e. central Africa) and West Africa are compared with the third and fourth ICA modes (i.e., with their ICs), respectively. Note, to recover the amplitudes of NDVI for each localised region (e.g., NDVI mode 1 localised over the Sudano-Sahel), each temporal pattern is jointly interpreted with the corresponding spatial pattern.

NDVI modes over the Sudano and Central Sahel indicate relatively strong annual and multi-annual variations, respectively (IC1 and IC2, Fig. 3, right). Generally, the first NDVI mode is consistent with the dominant patterns of rainfall and TWS in West Africa as shown in a recent study (Ndehedehe et al., 2016a). This presents a preliminary picture of both rainfall and TWS as hydrological drivers of surface vegetation over the Sudano-Sahel belt. As the main focus of this section is on the temporal assessment of the leading modes of NDVI with TWS, the relationship of the former with rainfall is also explored. Spatially averaged rainfall over West Africa (cf. Fig. 1a) is strongly associated with NDVI temporal evolutions in the Sudano-Sahel

Table 2: Temporal relations (r/R^2) of NDVI with those of TRMM and TWS in West and Central Africa as observed in the independent modes of variability in Fig. 3. Correlation coefficients are significant at the 95% significant level using the Student t-test except for those marked with *. It should be noted that both TRMM-based precipitation and TWS are aerial averages of those regions, which is deemed consistent with the localised NDVI patterns obtained from the statistical decomposition.

S/N	Modes	NDVI vs TRMM		NDVI vs TWS	
		r	R^2	r	R^2
1	IC1	0.77	0.59	0.68	0.47
2	IC2	0.69	0.48	0.72	0.52
3	IC3	0.11*	0.00*	0.01	0.00*
4	IC4	0.32	0.10	-0.67	0.44

(IC1, Fig. 3 and Table 2) compared to the relationship of averaged rainfall over the Central Sahel with NDVI (IC2, Fig. 3 Table 2). This shows a strong response of vegetation to rainfall in the Sudano and semi-arid Sahel regions. Over the Central Sahel (IC2, Fig. 3), the temporal variation of TWS showed a relatively strong association with NDVI while in the Sudano-Sahel area (IC1, Fig. 3), TWS showed slightly less agreement with NDVI when compared to rainfall (Table 2). Their coefficient of determination (R^2) show that TWS explains 47% while rainfall explains 59% of the annual signals in NDVI over the Sudano-Sahel belt (IC1, Fig. 3, Table 2). In the Central Sahel (IC2, Fig. 3, Table 2), TWS explains slightly higher portion of the variability in NDVI ($R^2=52\%$) than rainfall ($R^2=48\%$). This explicit relationship between TWS and vegetation condition in the Central Sahel suggests TWS could serve as a hydrological control for assessing vegetation response to changes in hydro-climatic conditions. This is true since it is a more direct measure of water availability in a given ecosystem, complementing precipitation that provides an indirect observation of water availability.

Notably, the Central Sahel is semi-arid, characterised by mostly grasslands, open shrublands, and croplands, with annual rainfall ranging from 700 mm to less than 200 mm during the studied period (cf. Figs. 1b and d). Given that the Central Sahel is characterised by high land surface temperatures since it is somewhat close to the Sahara Desert, vegetation growth and the green-up of plant cover in this region will be largely restricted by soil wetness and pedological conditions such as infiltration and water holding capacity. High evapotranspiration rates emanating from land surface temperatures decreases the amount of net precipitation (precipitation minus evapotranspiration), and may contribute to the lower proportion of variability explained by rainfall. With such environmental conditions, TWS is likely to be driven

by changes in soil wetness in such areas. GRACE-derived TWS changes would then be a more reliable and available surrogate for soil wetness, which is an ideal land surface state variable to examine the impacts of the climate system on vegetation changes. Nevertheless, the results for NDVI mode 1 indicate that rainfall is still a more viable driver of vegetation changes in the Sudano-Sahel region (IC1, Fig. 3). The impact of rainfall on temporal NDVI evolutions in the Sudano-Sahel belt may be justified given that it is largely an agricultural ecosystem (Fig. 1b) and interestingly, heavily dependent on rainfall. Exceptions to this may include some of the selected catchments where observed temporal relationships (NDVI vs rainfall) based on annual aggregations show otherwise (Fig. 2c-h).

Furthermore, the third mode of NDVI variability, accounting for 8.1% of the total variability indicates multi-annual vegetation changes in the Congo basin (IC3, Fig. 3). The fourth mode showed NDVI annual variability in some coastal countries with an opposite phase in the south of Central African Republic (CAR) and north of Cameroon (IC4, Fig. 3), and corresponds to 4.4% of the total variance. In the Congo basin area (cf. Fig. 1a), observed NDVI variability showed a rather poor relationship with TWS while averaged rainfall indicated a positive correlation (IC3, Fig. 3 and Table 2). Considering the role of TWS as a low-pass filter of precipitation, this may also point towards a phase lag between TWS and NDVI (IC3, Fig. 3). But the last NDVI mode (IC4, Fig. 3) showed a statistically significant negative association with average TWS over West Africa and may be caused by a phase shift of 0.5 years. We also observed that average rainfall over the same area indicated a positive association (Table 2). Other complementary perspectives regarding complex environmental processes in the area may be related to the influence of land use change, surface albedo alterations, uncontrolled deforestation and bush burning, amongst other factors (e.g., Mahe et al., 2013, Paturel et al., 2003, Li et al., 2007, Favreau et al., 2009, Leduc et al., 1997). For example, from the land cover data analysed, we found that temporally, the aerial extent (km^2) of several land cover units declined (savanna, closed shrublands, mixed and evergreen forests) while others showed marked fluctuation between 2002 and 2007 (not shown). Whereas this is rather suggestive of land cover dynamics as key secondary drivers of temporal vegetation dynamics in the region, aforementioned studies in Section 1 supports this notion. These impacts of land use change and those of climate variations however, in the context of how they may primarily determine the trajectory of prospective future changes in the vegetation system of WCA, is a subject for further consideration in subsequent studies.

Figure 4: Comparing the time series of temporal variations of NDVI, TWS, and rainfall averaged over West Africa and selected basins/catchment areas (Congo basin, Lake Chad basin, and southern Mali) after removing the mean of the period (2002–2013). (a-b) Monthly temporal relationship of NDVI with TWS and precipitation and (c-d) association of monthly residuals in NDVI with those of TWS and precipitation over West Africa. (e-j) Regression fits for NDVI with TWS and precipitation in the selected basins and catchment. The multi-linear regression analysis was used to estimate the residual parts of each data by separating the harmonic components (annual and semi-annual) from the data.

5.1.3. *The influence of TWS and rainfall on regional dynamics of surface vegetation*

The temporal patterns of monthly terrestrial water storage (TWS) show a rather similar association with NDVI as with rainfall. Specifically, TWS and rainfall indicate correlations of 0.74 and 0.68, respectively with NDVI (Figs. 4a and b, Table 1). The residuals of TWS showed weak associations with those of NDVI unlike rainfall whose residuals indicated no association with NDVI (Figs. 4c and d). The MLRA results of Figs. 4a-b were compared with singular spectral analysis (Ghil et al., 2002) of NDVI, rainfall, and TWS time series over West Africa. Although the results of singular spectral analysis are not shown, overall, they are somewhat consistent with those of MLRA, indicating that temporal series of TWS are more associated with NDVI compared to rainfall. In Figs. 4e-j, both TWS and rainfall explained significant variability in observed NDVI over southern Mali, Lake Chad basin and Congo basin (except for TWS) with TWS in the Lake Chad basin explaining the highest variability ($R^2 = 69\%$). At the annual scales, TWS and rainfall averaged over West Africa to some degree are less associated with NDVI given their relatively low correlations with NDVI (Table 1). Because of the diversity in landscapes, climate patterns, and ecosystem structure, poor annual associations of this nature could result from data averaging and aggregation over the region. Similar analysis for selected catchments in WCA showed that TWS and rainfall have stronger associations with NDVI in southern Mali while only TWS is better associated with NDVI in Lake Chad basin (Table 1). Also, the ‘human-induced signal’ such as increase in cropping areas, land use change, and a reduction in fallow period as indicated by Dardel et al. (2014), in our view, could significantly affect the temporal evolutions of surface vegetation, leading to poor correlations of NDVI with TWS and rainfall.

Evaluating the monthly temporal patterns of NDVI with those of TWS and rainfall over WCA, it becomes rather apparent that the monthly and inter-annual variability of NDVI are both explained by TWS and rainfall (Figs. 4a-j). Considering the relatively strong correlations of TWS with NDVI in particular, it can be argued that TWS appear to be more dependable than rainfall in its capacity to highlight the water-driven changes in the temporal evolutions of surface vegetation greenness in southern Mali and the Lake Chad basin (Figs. 4g and i). Over West Africa, the relationship is somewhat similar as TWS explains about 55% or $r = 0.74$ (Fig. 4a) of the changes in monthly NDVI while rainfall explains about 46% or $r = 0.68$ (Fig. 4b and Table 1). This picture accentuates the relative capacity and potential of TWS as a hydrological state variable for monitoring climatic influence on the temporal variations in

surface vegetation greenness over West Africa. This narrative may change nonetheless, when the association between NDVI and TWS is evaluated based on a grid by grid comparison. Such changes may be subject to the complexity in ecosystem interactions and environmental factors (e.g., irrigation, use of chemical fertilizers, etc.). Also note that results presented in Figs. 4e-j are region-specific cases where TWS shows stronger association with NDVI. As the grid-based relationship in Section 5.2 indicates, rainfall overwhelmingly agrees with NDVI in much of WCA as opposed to TWS.

5.2. Spatial relations of GRACE-TWS, rainfall, and groundwater variability to NDVI

5.2.1. Response of monthly NDVI to hydrological conditions at pixel scale

NDVI shows relatively strong sensitivity to changes in terrestrial water storage (TWS) and rainfall mostly in the Sahel zone (i.e., Sudano and Sahel belt) (Fig. 5), consistent with the results in Section 5.1.2. Evaluating the pixel scale relationship, rainfall shows statistically significant correlations ($\alpha = 0.05$) with NDVI in about 90% of WCA (includes non-linear response) during the 2002 – 2013 period compared to TWS (70% of the region) (Figs. 5a-b). From the spatial distribution of the correlation coefficients, rainfall has a much wider spread of positive correlations than TWS. Strong positive spatial correlations of TWS with NDVI are mostly found along the Sudano-Sahel belt (Fig. 5a). But rainfall indicated significant association with NDVI beyond the Sahel, extending to the Sudano and Central African region (Fig. 5b). It is observed that regions characterised by savannas, croplands (natural vegetation), and grasslands (cf. Fig. 1b) are the dominant biomes in this Sahel zone where NDVI indicates a considerable spatial association with rainfall and TWS. Our contemporary understanding of the African eco-hydrological processes indicates that the preponderance of observed positive correlations of NDVI with TWS and rainfall are predominantly found in the Sudano-Sahelian ecosystems, where total NDVI variability as shown in the first mode of Fig. 3 is apparently the highest (51.4%). Rainfall however, shows significant positive association with NDVI in regions that encompasses all the dominant modes of NDVI variability observed in Fig. 3.

Looking closely at Figs. 5a-b, TWS in some parts of West Sahel (e.g., Gambia, Guinea, Guinea Bissau, southern Mali) and some locations in Lake Chad basin (parts of northern Nigeria, southern Niger, and southern Chad-Fig. 1a) show higher correlations with NDVI compared to rainfall. In the northern flank of Niger, the positive correlations in Fig. 5a indicate that NDVI still oscillates in some arid ecosystems and shows agreement with TWS unlike the non-linear response indicated by rainfall (Fig. 5b). Whereas NDVI in other regions of WCA

are better correlated with rainfall, the potential of GRACE-derived TWS as a hydrological control for ecosystem performance, at least in these region-specific cases is also highlighted. Plant cover ideally responds to land surface conditions. Hence, change in soil conditions and possible changes in land surface temperature in these ecosystems may play a major role in the observed association of NDVI with TWS and rainfall. We also found relatively strong positive correlations of NDVI with rainfall in Gabon and some areas of the Congo basin, where evergreen broadleaf forest and wetlands are largely predominant. Other coastal countries in West Africa (e.g., Liberia, Côte d'Ivoire, and Sierra Leone) however, show relatively poor and negative correlations despite having almost similar climate patterns, vegetation and edaphic formations as the countries in the Congo basin.

Figure 5: Spatial correlations of monthly NDVI with (a) TWS (2002 – 2013), (b) TRMM-based precipitation (2002 – 2013), and (c) WaterGap model groundwater (2002 – 2009) over West and Central Africa. Only statistically significant correlations ($\alpha = 0.05$) are indicated.

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An assessment of vegetation response to rainfall and TWS show some spatial limits and complexities. For example, be it rainfall or TWS, the correlations are either generally low or negative in humid (coastal areas) and extreme arid environments (Central Sahel). Apparently, high correlations are mostly present in regions of considerable seasonal change (cf. IC1, Fig. 3) rather than regions with little seasonal change such as the tropical coastal regions where NDVI-TWS is extremely low or non-existent in some cases (insignificant). Relatively weak associations of TWS and rainfall with NDVI were found even in ecosystems with annual rainfall

459 exceeding 2500 mm (areas with very little seasonal change as seen in IC1, Fig. 3) while those
 460 with annual rainfall less than 1000 mm (areas with considerable seasonal change-IC1, Fig. 3)
 461 indicated strong association with NDVI. The result of different vegetation having different
 462 water critical points may also account for this. The waterlogged soils of humid coastal WCA
 463 countries (e.g., Liberia, southern Côte d'Ivoire) may suggest that vegetation development
 464 is mostly a function of pre-existing soil conditions as argued earlier. Consequently for such
 465 ecosystems, rainfall is not primarily a factor for vegetation growth. Similar relationship is also
 466 observed with TWS in the coastal areas lying in the evergreen broadleaf forests (cf. Fig. 1b),
 467 where there was no association with NDVI (Fig. 5a). This probably is due to the fact that
 468 TWS changes here are the result of a weak seasonal signal. But in the Sahel and Sudano
 469 belt, rainfall may be perceived as a major indicator to NDVI, hence their strong agreement
 470 (Fig. 5b). Consistent with this study, strong and significant positive correlations of NDVI
 471 with rainfall were reported recently for the Sudano-Sahel region as against the wetland and
 472 irrigated areas, which produced weak correlations (Georganos et al., 2017). However, roots
 473 exploration, the adaptability and tolerance of plants to arid conditions and changes in the
 474 composition of species richness may impact such relationship (e.g., Chen et al., 2014, Zhou
 475 et al., 2014).

476 The correlation result in Fig. 5c indicates that model groundwater is well associated with
 477 NDVI in southern Mali and much of the Sahel and Sudano belt. Based on the response of NDVI
 478 to TWS and groundwater (e.g., southern Mali, Senegal, Gambia, south-west Guinea, northern
 479 Nigeria, etc.) in Figs. 5a and c, it is argued that surface vegetation in these ecosystems respond
 480 to water availability in all catchment stores, including groundwater. Huber et al. (2011) had
 481 reported the restriction of soil moisture in the southern Sahel regions as a driver of higher
 482 woody vegetation canopy. Several woody plants remain photosynthetically active during the
 483 year as opposed to other plants that are only green during rainy season (see, Brandt et al.,
 484 2016). It is therefore more likely that TWS may be the most prominent driver(s) of vegetation
 485 dynamics in some parts of the semi-arid Sahel where photosynthetic activities can be seen
 486 even during periods of limited or no rainfall. As the Sahel region is well known for frequent
 487 droughts owing to the impact of climate variability (e.g., Ndehedehe et al., 2016b, Nicholson
 488 et al., 1998), roots exploration and the adaptability of some plants to long dry periods validates
 489 such argument. Going by the response of NDVI to groundwater (e.g., Guinea Bissau, southern
 490 Mali, etc.) in Fig. 5c, TWS would be a substantive driver of vegetation dynamics as it better
 491 represents the rooting depth of any vegetation, given its water column, which extends to the

492 unsaturated zone. Although more than 30% of global biodiversity benefit from groundwater
 493 (Fan et al., 2013), extreme water requirements in water limited ecosystems caused by increased
 494 evapotranspiration, prolonged dry seasons, and rainfall deficits (Ndehedehe et al., 2018c) can
 495 modify the structural properties of vegetation communities, making them even more dependent
 496 on groundwater. The strong TWS-soil moisture relationship (not shown) in a typical Sahelian
 497 catchment such as the Lake Chad basin suggest that soil moisture is the principal component
 498 driving observed changes in the GRACE water column in the region. This presents TWS as
 499 a suitable soil moisture surrogate that may be considered as suitable and readily available
 hydrological control for surface vegetation in semi-arid regions.

Figure 6: Correlations of NDVI (2003 – 2013) with TRMM-based precipitation and TWS at pixel scale (spatial pattern) for seasonal periods (January, February, and March-JFM; March, April, and May-MAM; April, May, and June-AMJ; July, August, and September-JAS; September, October, and November-SON; October, November, and December-OND). (a) Correlations between seasonal NDVI and rainfall and (b) correlations between seasonal NDVI and TWS. These seasonal classifications (see Supporting Information for the NDVI groupings) are also based on crop and rain seasons in West and Central Africa.

5.2.2. Seasonal relations of NDVI to terrestrial water storage and rainfall

Seasonal variability of NDVI was also compared with terrestrial water storage (TWS) and rainfall in order to assess their interrelationships. As NDVI correlations with rainfall during dry season introduces larger bias (Huber et al., 2011), these seasonal evaluations are required to provide a more robust assessment. Correlations between NDVI and rainfall tend to be high in the Sahel zone and some coastal countries during the October-November, April-June, September-November, and March-May periods while very little association is found in the July-September and January-March periods (Fig. 6a). But TWS shows a higher relation in October-November while other seasonal periods indicate significant relationships with NDVI mostly in the Sahel zone except during the March-May period (Fig. 6b). Indeed, an overall assessment of the relation of the monthly and seasonal NDVI with those of rainfall and TWS (i.e., based on the respective grids) indicate that rainfall unarguably, provides a hydrological control on NDVI phenology in much of the sub-continent. A similar relationship (i.e., NDVI and rainfall) was observed by Nicholson et al. (1990) in the Sahel region, consistent with our result here. However, rainfall is restricted in the growing season (e.g., July-September) as a driver of vegetation dynamics unlike TWS (Fig. 6b). The seemingly poor performance of rainfall as a driver of vegetation dynamics during the growing season is consistent with the findings of Huber et al. (2011) who also argued that the dry seasons introduce bias in the observed relationship (rainfall vs NDVI) because while NDVI still oscillates during such periods, rainfall does not. Rainfall certainly shows wider spread of positive correlations during the October-November period (Fig. 6a) compared to TWS (Fig. 6b). TWS has shown linear relationships (positive correlations) nonetheless, in some locations (e.g., northern Niger) where rainfall indicated negative correlations or no association. Although TWS is also strongly associated with NDVI in much of WCA similar to rainfall, some locations exist where NDVI, either at monthly or seasonal scales, demonstrates relatively strong and consistent sensitivity to TWS compared to rainfall (Figs. 5 and 6). It is our view that these region-specific cases, which include the West Sahel (e.g., southern Mali and Guinea) and the Lake Chad basin (e.g., north-east Nigeria and southern Chad), are typical examples of where TWS provides better hydrological controls for the water driven variability in vegetation. In these specific cases, TWS can serve as a strong complement to rainfall for the mapping of hydrological impacts on surface vegetation, given the lack of in-situ data and the bureaucracies involved in its acquisition in the region. TWS in these landscapes would be more reliable than precipitation as soil moisture

533 surrogate to monitor water availability for the development of surface vegetation. This is
 534 because, technically, GRACE-derived TWS changes would be mostly driven by soil wetness
 535 in the unsaturated soil moisture zone. Yang et al. (2014) argued that these zones are more
 536 readily affected by changes in climate than the saturated zones. In the Lake Chad basin,
 537 for example, changes in TWS would largely emanate from this catchment store (unsaturated
 538 zone and to some degree saturated zone during extreme hydrological drought periods), as
 539 groundwater abstractions are unknown and water loss is mostly through evapotranspiration
 540 (e.g., Ndehedehe et al., 2018c).

Figure 7: Maximum correlations of NDVI with TRMM-based precipitation and TWS for the common period (2002 – 2013). (a) Maximum correlations between NDVI and TWS (b) maximum correlations between NDVI and rainfall (c) time lag for which maximum correlation is observed between NDVI and GRACE-TWS and (d) time lag for which maximum correlation is observed between NDVI and rainfall.

5.2.3. *Lag response of NDVI to rainfall and terrestrial water storage and the influence of land surface conditions*

The observed relationship of NDVI with terrestrial water storage (TWS) in the specific catchments identified in the preceding section is further confirmed from the analysis of lagged correlation using the cross correlation method. These results (i.e., the time lag for maximum correlations) apparently show stronger correlation coefficients in the TWS-NDVI relationship (Fig. 7a) in these catchments when compared to NDVI-rainfall relationship (Fig. 7b). With an estimated time lag of 1 month (Fig. 7c), the variability in surface vegetation greenness can fairly be predicted in the Lake Chad basin using TWS. As indicated in Fig. 7c, TWS lags and leads NDVI by approximately one month in the Sahel and Guinea coast zones, respectively. Apart from other arid ecosystems in the Central Sahel where TWS also leads NDVI, probably due to plants adaptability, composition and structure, NDVI shows generally, a lead of one month and to some degree a zero lag in the Sahel zone. On the other hand, rainfall is more associated with NDVI in much of WCA than TWS (Fig. 7b), and shows a one month lead except for areas where the biomes are predominantly broadleaf forest, indicating a zero lag (Fig. 7d).

Unlike rainfall, TWS is a rather weak driver of vegetation dynamics in the Congo basin (Figs. 5a, 6b, and 7a). The distribution of the cross correlation coefficients indicate no association between NDVI and TWS in large parts of the Congo basin (Fig. 7a). But trends in TWS and ET are somewhat consistent with NDVI in extreme southern part of the Congo-DRC region, unlike rainfall (Figs. 8a-d), suggesting the potential impacts of other factors on the NDVI-TWS relationship in Congo basin. Apart from increased evapotranspiration (Fig. 8d) and a likely human footprint, poor spatial relations of TWS with NDVI even at maximum correlations could be due to the fact that TWS in the Congo basin, is mostly driven by runoff as the multi-annual variation in TWS over the Congo basin is strongly associated with river runoff (Ndehedehe et al., 2018b). Although no spatial relations exist between NDVI and TWS in the Congo basin (except weak positive correlations during the March-May period-Fig. 6b), the negative trends in TWS of the Congo basin (obtained from Sen's estimate), which agree with those of NDVI in the extreme southern part of the Congo-DRC region (Fig. 8a and c), suggest TWS can be used to monitor the impacts of climate change on vegetation dynamics. However, the negative trends in TWS around some sub-regions of the Congo basin was attributed to deforestation (Ahmed et al., 2014) and further confirms that a combination of

land cover transitions and climatic variations may impact on the hydrological response of a drainage basin.

Figure 8: Observed spatial trends based on Sen’s estimate for (a) NDVI, (b) TRMM-based precipitation, (c) TWS, and (d) evapotranspiration during the 2002 – 2013 period. The trends in TRMM, TWS, and evapotranspiration are in mm/month.

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575 In Fig. 8d, the Lake Chad basin show considerable increase in evapotranspiration. This
 576 increase in evapotranspiration in much of the basin is an indication of high evaporative de-
 577 mand (the rate of water loss from a wet surface). Reduced alimand and precipitation
 578 deficits in relation to large outgoing water flux such as evapotranspiration may lead to large
 579 water budget changes and hydraulic behaviour of the basin that impacts on NDVI-rainfall
 580 relationship. Given that atmospheric conditions regulate the life span of canopy phenology,
 581 and both leafing and reproductive phenophases of Sahelian ecosystems (e.g., [Seghieri et al.,](#)
 582 [2012](#), [Do et al., 2005](#)), TWS would better account for plant water availability. This is largely
 583 because GRACE-TWS provides an overall picture of the water budget and accounts for avail-
 584 able freshwater changes in the ecosystem, regardless of catchment and landscape effects (e.g.,
 585 soil and vegetation types) that may have potential impact on hydrological processes. Add
 586 to this, widespread drought tolerant species resulting from extended and prolonged drought
 587 periods in the semi-arid ecosystems could lead to transformative relationship and changes in

the composition of species richness. This creates a complex response of surface vegetation to hydrological conditions due to the mechanics of water use in the region (e.g., Huber et al., 2011). This, for example, is evident in the Sahelian ecosystems that are considerably associated with groundwater (Fig. 5c). Thus, GRACE-derived TWS would be a more suitable hydrological indicator to highlight the impact of climate variability on vegetation dynamics in the basin and other ecosystems where similar relationship is observed.

6. Conclusions

This study provides an overview of the utility of Gravity Recovery and Climate Experiment (GRACE) derived terrestrial water storage (TWS) and rainfall as drivers of vegetation dynamics in West and Central Africa (WCA). To support the mapping of groundwater dependent ecosystems, the relationship between NDVI and model groundwater was also examined. The conclusions from the study are summarised as follows:

- (1) The temporal relations of NDVI with those of TWS and rainfall suggest that the monthly and inter-annual variability of NDVI are both explained by TWS and rainfall in the semi-humid and arid ecosystems of WCA. But in region (West Africa) and catchment specific cases (southern Mali and Lake Chad basin), TWS explained more of the water-driven changes in the temporal evolutions of surface vegetation greenness than rainfall. However, in the Congo basin, the NDVI-TWS temporal relationship is statistically insignificant ($\alpha = 0.05$) as opposed to the temporal relationship between NDVI and rainfall that is considerably strong. With evapotranspiration as a major source of water loss and the Congo river being a strong component of observed variations in GRACE hydrological signal, land surface feedbacks and interactions would be rather complicated. Combining this with recent droughts in the Congo basin, the NDVI-TWS relationship is more likely to be unclear.
- (2) TWS and rainfall are strongly associated with NDVI in the Sahel zone (Central and Sudano) when the relationship is evaluated at pixel scale (spatial relations). Rainfall in particular shows stronger association with NDVI in much of WCA (except for some of the Guinea coast countries) than TWS (i.e., 90% of WCA showed significant relationships between NDVI and rainfall as opposed to TWS-70%). The largest spread of positive correlations of NDVI with TWS and rainfall however, are found during the October-November window, though the spread of positive correlations extends to the Congo

basin for the NDVI-rainfall relationship. But some catchments also exist (e.g., north-east Nigeria and southern Chad) where NDVI demonstrates relatively stronger and consistent sensitivity to TWS when compared to rainfall.

(3) Although NDVI spatial relationship with TWS and rainfall (monthly) in the arid Sahel and some wetland areas in the Guinea coast are generally significant, they are largely weak and negative. A number of factors ranging from land surface processes and human disturbance (e.g., land use change) might be responsible for this. However, although not fully explored in this study, we insinuate that based on the time series of observed MODIS land cover between 2002 and 2007, degradational transitions in land cover, and agricultural expansion are key secondary elements that drive the vegetation dynamics in these locations. And for the lack of forest conservation policies in several parts of the region, it is more likely that prospective future changes in the vegetation system of humid tropical WCA could be largely controlled by the trajectory of human disturbance of the ecosystem.

(4) Contemporary understanding of the African eco-hydrological processes indicates that the preponderance of observed positive correlations of NDVI with TWS and rainfall are predominantly found in the Sudano-Sahelian ecosystems, where total NDVI variability as shown in the dominant pattern is apparently the strongest (51.4%). Rainfall however, shows significant positive association with NDVI in regions that encompasses the four dominant modes of NDVI variability identified in this study. Moreover, there are indications that some of the Sahelian vegetation may depend on groundwater as strong correlation between NDVI and WaterGap groundwater model has been observed. This relationship (NDVI vs groundwater) also coincides with some of the site-specific cases (mostly semi-arid) in (ii) above where NDVI shows consistent response to TWS than rainfall. Since NDVI still oscillates in these arid ecosystems despite having limited or highly variable rainfall, TWS may be a better hydrological control for the water driven variability in surface vegetation. As a key component of sustainable groundwater management, relevant government institutions seek to protect groundwater dependent ecosystems. Hence, the statistical relationships developed in this study are considerably helpful in addressing the somewhat difficult task of mapping and delineating groundwater dependent vegetation communities.

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7. Supporting Information: Spatial patterns of seasonal NDVI

A quick assessment of NDVI distribution show that relatively strong NDVI values are observed in the coastal countries during the January-March, April-June, and July-September periods (Supporting Information, Fig. 9). Conversely, low NDVI values are observed during the September-November and October-December periods (Supporting Information, Fig. 9). NDVI still oscillates during dry seasons along the coastal countries of West and Central Africa (WCA). This can be seen, for example, in the January-March period in Liberia, Côte d'Ivoire, southern Ghana, and Cameroon where despite receiving relatively low rainfall during the period (dry season) indicate high NDVI values. This perhaps is due to the presence of permanent wetlands and huge evergreen broadleaf forests that thrives in water logged soils (Fig. 1b). Consequently, rainfall may not be sufficient in monitoring vegetation conditions in such areas as the vegetation and forest formations are mostly sensitive to pedological conditions that are in the root zones. Apart from soil type, climate variability play key roles in the spatial and temporal distributions of surface vegetation in WCA. Hence, evaluating the potential of GRACE-TWS as a hydrological indicator as opposed to other physical variables (precipitation, soil moisture) in providing useful information regarding our understanding of the spatial and temporal variations of vegetation dynamics is warranted. To this end, the spatial and temporal variations of monthly, annual, and residual NDVI anomalies over West Africa and selected catchments (Congo basin, Mali, and Lake Chad basin-Fig. 1a) are compared with those of TWS and precipitation. The selected catchments are tentative test beds employed to examine the relationship of NDVI with TWS and rainfall in different climatic domain. In other words, they are so chosen to be representative of humid, semi-arid and arid characteristics of tropical WCA systems. Notably, exploring the water driven variability of surface vegetation at catchment scale could be useful in advancing process-level insight into the vegetation or climate characteristics that modulate the couplings of NDVI with different hydrological indicators.

Figure 9: Average seasonal NDVI distribution over WCA, otherwise known as sub-Sahara Africa for the period between 2002 and 2013. The seasonal classifications are based on crop and rain seasons in WCA and are described as: January, February, March; March, April, and May; April, May, and June; July, August, and September; September, October, and November; October, November, and December.

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