Ecological Indicators 88 (2018) 51–62

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Is terrestrial water storage a useful indicator in assessing the impacts of climate variability on crop yield in semi-arid ecosystems?

Christopher E. Ndehedehe[a,b,*], Nathan O. Agutu[a], Onuwa Okwuashi[b]

[a] Department of Spatial Sciences, Curtin University, Perth, Western Australia, Australia
[b] Department of Geoinformatics and Surveying, University of Uyo, P.M.B. 1017, Uyo, Nigeria

ARTICLE INFO

Keywords:
Food security
Lake Chad basin
Rainfall
Agriculture
Climate variability
Sahel

ABSTRACT

The productivity of global terrestrial ecosystems, especially in rain-fed agricultural systems and water-limited semi-arid ecosystems is largely restricted owing to climate-induced freshwater variability. In this study, Lake Chad basin (LCB) is selected as a tentative test bed to examine the utility of terrestrial water storage (TWS) inverted from Gravity Recovery and Climate Experiment (GRACE) measurements as a useful indicator in assessing the impacts of climate variability on annual crop yields (2003–2013) in a semi-arid ecosystem. Regression results show that changes in the temporal series of GRACE-derived TWS in LCB explained significant and higher proportion of variation ($R^2 = 55\%$, 39%, and 32%, $p < 0.05$) in cashew nut, potatoes, and cowpea yields, respectively, compared to rainfall ($R^2 = 2\%$, 1%, and 7%, respectively). Rainfall on the other hand, explained a higher ($R^2 = 32\%$) variability in soybeans than TWS ($R^2 = 2\%$). Model soil moisture indicated significant relationship ($p < 0.05$) with cowpea ($R^2 = 48\%$), onions ($R^2 = 44\%$), and cashew nuts ($R^2 = 30\%$) somewhat similar to TWS. TWS nonetheless, showed relatively stronger and significant associations with four crops (i.e., cashew nut, potatoes, cowpea, and rice) than with soil moisture (except cowpea) and rainfall. By integrating TWS with rainfall as input variables to model crop yield data in a neural network system, the input variables are related to crop yield and showed some predictive potentials ($r = 0.89$ for cashew nut vs TWS/rainfall, $p < 0.05$), which can be improved considerably when longer times series of the data (especially TWS) are available for robust network training, testing, and validation. Large proportions of Africa and other non-industrialised regions of the world are heavily reliant on rainfed agriculture. Hence, multi-model climate forecasting studies in these regions can leverage on TWS not only as a soil moisture surrogate to assess the impacts of climate change on future scenarios of food production patterns, but as critical and resourceful input to food security analysis.

1. Introduction

Unfavourable hydro-climatic conditions in the Sahelian countries of West Africa, arguably have contributed to famine, decline of primary production, widespread desertification, and land degradation (see, e.g., Ndehedehe et al., 2016c; Knauer et al., 2014; Shiferaw et al., 2014; Tucker et al., 1991) and have resulted in several negative impacts on the socio-economic systems of the region. These impacts were the primary triggers of several ecosystem assessment based on Normalised Difference Vegetation Index (NDVI) and key hydrological indicators, e.g., rainfall and soil moisture (see, e.g., Andam-Akorful et al., 2017; Dardel et al., 2014; Jamali et al., 2014; Boschetti et al., 2013; Huber et al., 2011; Louise et al., 2014; Huber et al., 2011; Begue et al., 2011; Herrmann et al., 2005; Knauer et al., 2014). However, complex hydrological processes such as the well known 'Sahelian paradox', where despite the severe drought conditions of the 1970s and 1980s, an extensive network of well observations revealed that groundwater resources and water table in Niger increased tremendously due to changes in land use, amongst other factors (see, e.g., Descroix et al., 2009; Favreau et al., 2009; Séguis et al., 2004; Leblanc et al., 1997; Leduc et al., 2001). This phenomenon, which has also been reported in several other Sahel regions of West Africa (e.g., Gal et al., 2017; Mahé and Paturel, 2009; Mahé and Olivry, 1999) coupled with the restrictions of rainfall and soil moisture as hydrological indicators on surface vegetation dynamics in some parts of West Africa (e.g., Boschetti et al., 2013; Huber et al., 2011; Begue et al., 2011; Herrmann et al., 2005; Olsson et al., 2005), are notable challenges that warrants further understanding of the region's eco-hydrological processes and the impacts of climate variability.

In West Africa, a plethora of region and basin-specific studies have

---

[*] Corresponding author at: Department of Spatial Sciences, Curtin University, Perth, Western Australia, Australia.
E-mail address: c.ndehedehe@postgrad.curtin.edu.au (C.E. Ndehedehe).

https://doi.org/10.1016/j.ecolind.2018.01.026
Received 28 September 2017; Received in revised form 11 January 2018; Accepted 15 January 2018

employed the latest satellite geodetic programme, Gravity Recovery and Climate Experiment (GRACE, Tapley et al., 2004) as a vital tool in hydrological research. These studies focused on a wide range of applications, e.g., in droughts (e.g., Ndehedehe et al., 2016c,b); terrestrial water budget closure (e.g., Ferreira and Asiah, 2015); hydrological characteristics, sub-surface water storage, aquifer system processes (see, e.g., Ndehedehe et al., 2016a, 2017a; Ferreira et al., 2014; Gonçàlves et al., 2013; Nahmani et al., 2012; Henry et al., 2011; Hinderer et al., 2009); and evaluating the contributions of global climate teleconnections on regional dynamics of terrestrial water storage-TWS (an integrated sum of changes in catchment stores, e.g., groundwater and soil moisture; canopy; and surface waters) (e.g., Ndehedehe et al., 2017b). Given that the observed relationship between long term soil moisture changes and variations in some Sahelian vegetation was found to be inconsistent (Huber et al., 2011), more insightful studies using GRACE observations might be useful to further assess water-related impacts on the region's terrestrial ecosystem.

Over mainland Australia, GRACE-observed TWS explained variations in surface vegetation greenness at both inter-annual and seasonal time scales (Yang et al., 2014) while its role in modulating vegetation response to temperature changes in Eurasia has also been reported (A et al., 2015). This suggests its utility as a hydrological indicator of ecosystem performance in water limited ecosystems and Arctic biomes. However, the potential of GRACE-derived TWS in assessing the response of annual crop yields to the impacts of climate variability in data deficient, semi-arid regions (e.g., the Sahel) has not been reported. As mentioned in Chen et al. (2014), agricultural development and the productivity of the world's terrestrial ecosystems depends largely on water availability. In societies where the agricultural production systems are considerably reliant on rainfall, and for semi-arid regions that are presumably water-limited ecosystems, water deficit and extreme hydrologic variability remains a major restriction not only to vegetation growth but crop production and economic output (see, e.g., Yang et al., 2014; Hall et al., 2014; Piao et al., 2010). Hydrological variability has been identified as one of the key factors with adverse effects on the economic growth of non-industrialised regions (e.g., Hall et al., 2014; Brown and Lall, 2006), and represents a significant challenge to food security and infrastructure development. Lewis (2017) recently pointed out that one major aspects of underlying systemic causes of acute food insecurity in Ethiopia is the high proportion of small scale farmers who are heavily reliant on rainfed agriculture. Similar to Ethiopia and other sub-regions in Africa, the sensitivity of West Africa's agricultural production system and economy to climate variability is well known (see, e.g., Shiferaw et al., 2014; Cenacchi, 2014; Megersa et al., 2014; Ramarohetra et al., 2013; Roudier et al., 2011; Verdin et al., 2005; Vierich and Stoop, 1990). The strong variability of the West African Monsoon (WAM) on different time scales (e.g., inter-annual and multi-decadal), which brings about 70% of the annual rainfall (e.g., Sultan and Gaetani, 2016; Janicot, 1992) may impact adversely on agricultural systems, resulting in food insecurity and low national income. Because of this strong variability in the WAM system and large uncertainties and bias in regional climate projections (e.g., Todd et al., 2011; Roudier et al., 2011; Schuol and Abbaspour, 2006; Landerer and Swenson, 2000), quantifying the impacts of climate variations on agricultural yield is challenging.

While it is essential for government institutions to make informed and evidence-based decisions on appropriate indicators that will address specific policy issues relevant to food security governance (see, Pérez-Escamilla et al., 2017), understanding factors that impact on food availability is also critical. As mentioned in Brown and Lall (2006), one of the challenges to food production and national income is rainfall variability. According to Vörösmarty et al. (2005) who studied geospatial indicators of water stress in Africa, 25% of Africans are already experiencing water stress while an estimated 13% are direct recipients of drought-related stress once each generation. These indicators of water stress could have significant impact on a considerable proportion of Africa's agricultural biomes, which are mostly found in arid regions. For those regions where agricultural systems are devoid of sophistication yet account for a significant proportion of the gross domestic product (GDP), water stress and increased rainfall variability could translate to food insecurity, social conflicts, and poverty.

Cenacchi (2014), for example, noted that drought is a major constraint for crop and livestock production in Africa and across Asia. In a compendium of 16 related studies over West Africa (see, Roudier et al., 2011 and the references therein), there is evidence that climate change impact negatively on crop yield. Further, quasi-periodic phenomenon such as the El-Niño Southern Oscillation (ENSO) episodes have shown statistically significant association with some crops in the Sahel region (e.g., Okonkwo and Demoz, 2014). It is even anticipated that the impacts of global warming in the future will impact negatively on subsistence farming in several African countries (Verdin et al., 2005). As most climate projections suggest, the result of drought intensity in some areas around the world may lead to risk of crop losses (Cenacchi, 2014). In West Africa where an estimated 70% of the world's cocoa is produced, Schroth (2016) noted that drought years caused by El-Niño episodes affected cocoa yields. In addition to this, it has been shown that ENSO play significant roles in the characteristics of extreme climatic conditions in West Africa (e.g., Ndehedehe et al., 2016b; Paeth et al., 2012; Nicholson et al., 2000), and largely contribute to the temporal and spatial distributions of TWS in the region (e.g., Ndehedehe et al., 2017b). The impacts of climate change on agro-ecosystems are mostly channelled through hydrological drivers such as precipitation, soil moisture, and available freshwater. Consequently, there is a further need to diagnose the suitability of GRACE-derived TWS in assessing the impacts of climate variations on crop yield, particularly when rainfall and soil moisture have shown some weakness in the semi-arid Sahel as indicators of water availability (e.g., Dardel et al., 2014; Huber et al., 2011; Olsson et al., 2005).

In this study, the potential of GRACE-derived TWS as a useful terrestrial moisture surrogate in mapping the impact of hydrological conditions on annual crop yield in the Lake Chad basin (semi-arid Sahelian region-Fig. 1) is examined. The assessment of GRACE-derived TWS with crop yield data has become necessary given the (i) restrictions of rainfall as a hydrological indicator on terrestrial ecosystems and regional land surface phenology (e.g., Knauer et al., 2014; Seghieri et al., 2012; Chen et al., 2014; Yang et al., 2014), (ii) uncertainties in water budget estimates (e.g., A et al., 2015; Zhang et al., 2009), (iii) the morphological and physiological adaptations of Sahelian vegetation, which results in complex water use mechanisms during the dry season (e.g., Guan et al., 2014; Seghieri et al., 2012; Huber et al., 2011), and (iv) lack of considerable investments in observational networks for ecological and hydrological applications.

2. Assessing the impacts of climate variability on food security in the Lake Chad basin

2.1. The region

The Lake Chad Basin (LCB) is the world's largest interior drainage basin covering an approximate area of 2,500,000 km^2, and supports an estimated 37 million people who depend on its water resources for economic and domestic purposes (e.g., Ndehedehe et al., 2016b and references therein). Geographically, the basin is seated in the transition zone between the Sahara Desert and the tropical Sudano Sahel region of West Africa. Specifically, it is located between latitudes 6°N and 24°N and longitudes 7°W and 24°E and is occupied by Lake Chad at the centre (Fig. 1). The impact of persistent and long drought episodes of the 1960s and 1980s in the basin resulted in a significant contraction of the Lake Chad surface area (see, e.g., Ndehedehe et al., 2016b; Wald, 1990; Birkett, 2000; Coe and Foley, 2001; Lebel et al., 2003; Lemoalle et al., 2012). Rainfall is annual, occurring mostly between July and September. The basin is one of the Sahel regions that is highly vulnerable to