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Understanding climate and land surface changes impact on water resources using Budyko framework and remote sensing data in Ethiopia

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Abstract

Climate change and land degradation are the two drivers playing a significant role in changing freshwater availability. Targeted intervention requires understanding the role of each driver and their spatial dominance. However, detangling the effects of these factors and identifying where each plays the most important role is still unclear. In this study, we used Budyko-like framework and remote sensing data to evaluate the spatial effects of climate and land surface changes on water availability in Ethiopia. At national level, the mean long-term annual runoff change after 20 years is positive (about 80 mm/year), and is equally accountable to climate change (50%) and landscape surface changes (50%). However, both the change and contribution of the two factors vary spatially. In northern (Tigray region) and southeastern (Somali region) Ethiopia, the contribution of climate change is larger than the land surface changes on water resources. Particularly in the southeastern part of the country (Somali region), 70% of the changes in water resources is attributed to climate change. In most areas of the country, the change in water resources due to land surface change is positive. The detail percentage contribution of the two factors on the water resource change for each administrative zone is provided.

Keywords: Budyko hypothesis, Climate variabilities and change, Land surface change, Surface water resources, East Africa, Sub-Sharan Africa

1. Introduction

Intensified hydrological cycle is one of the global challenges that affects water resource availability at various spatio-temporal scales (Jackson et al., 2001; Huntington, 2006; Wild et al., 2008; Gedney et al., 2014; He et al., 2017). Land surface change (e.g., soil erosion, anthropogenic land use and land cover changes including clearing and conversion of undisturbed forest and grassland ecosystems into agricultural land, etc.) and climate change are the dominant processes affecting the natural hydrological cycle (Foley et al., 2005; Li et al., 2009). Land surface change, which is mostly induced by human activities, affects hydrological cycle through modification of infiltration, interception, runoff and evapotranspiration (DeFries and Eshleman, 2004). Higher inconsistencies have been reported on the trends/directions on the impacts of climate change on hydrological system (Rind et al. 1992) in the past. Recent evidences, however, show consensus on the effects of climate change on the water cycle (e.g. Huntington, 2006; Gosling and Arnell, 2016). Rodell et al (2018) used GRACE data to characterize global freshwater availability and attribution of changes. However, owing to GRACE's coarse spatial resolution and short period (i.e. 10 years), proper attribution of freshwater change at local scale is difficult. In the last two decades, significant number of studies have established interesting frameworks in analyzing the effects of climate and land use change on water resources using models such as the Soil and Water Assessment Tool (SWAT) model (Nie et al., 2011; Lin et al., 2015; Kundu et al., 2017; Ghaari et al., 2010; Lin et al., 2015; Zeleke and Hurni, 2001; Getachew and Melesse, 2012; Zuo et al., 2016; Baker and Miller, 2013). The findings from these studies are nonlinear, with highest number of cases reporting that land use change resulting an increase in surface runoff and hydrological variability. The applications of complex hydrological models employed in these investigations were limited due to the challenges in calibration and validation, large data requirement, necessity for high spatial and temporal resolution datasets, as well considerable model uncertainties (Wang et al., 2013). Another limitation of these hydrological models for estimating the impacts of climate and land surface change on water cycle is that most models use constant model parameter values suggesting that watershed proprieties/parametrization representing functional relationship between model inputs (e.g. climate forcing) and model outputs (e.g. discharge) are time invariant (Munoz et al. 2013; Velázquez et al., 2015).

Despite numerous local scale (watershed) hydrological modelling studies, holistic understanding of local water resources in relation to the environmental system is largely lacking. Similarly, Harte (2002) also suggested the need for Darwinian approach to get deeper understanding of the hydrological systems for investigations involving larger landscapes. This approach, in contrast to the "Newtonian" (i.e. local-scale and physically-based hydrological modeling) approaches (Wagener et al., 2013; Thompson et al., 2013; Harman and Troch, 2014), focuses on understanding landscape behavior in changing condition without long gauging records and runoff-generation hydrological models, could potentially allow better understanding of the underlying climatic and landscape surface properties controlling the hydrological systems of larger landscapes.

One of the well-known example, and probably the most investigated Darwinian approaches is the Budyko (1974) framework, initially presented by Schreiber (1904) and OlDekop (1911).

Budyko hypothesis relates the long-term average and large basins' actual evapotranspiration (ET) to potential evapotranspiration (PET) and precipitation (P) in a semi-empirical model. Budyko hypothesis is further renewed whereby now many Budyko-like models are developed for various applications (e.g. Choudhury, 1999; Donohue et al., 2012; Fu, 1981; Wang and Zhou, 2015; Milly, 1994; Yang et al., 2008; Zhang et al., 2004, 2008; Moussa and Lhomme, 2016; Gerrits et al., 2009). In data and water scarcity area, Budyko framework is suggested to be useful tools for evaluating water resources (Gunkel and Lange, 2017). It has been used from global scale (e.g. Fang et al. 2016), to national or large river scale (e.g. Singh and Kumar, 2015), and small basin scale (e.g. Abera et al., 2017).

Ethiopia is characterized by high water risk (Gassert et al., 2014) due to recurrent drought and extreme events, as well as several biophysical and socio-economic constraints for sustainable agriculture production and food security. For instance, the water resource stress in the southeastern part (e.g. Somalia region) is mainly caused by recurrent rainfall shortages and changing climate. On the other hand, the highest effect in the central and western highlands of Ethiopia is mainly because of the combination of higher climate variability, and enhanced land use and land cover changes and land degradation (Hermans-Neumann et al., 2017). To curb the debilitating impacts of land degradation, climate variabilities and change on livelihood of the resource-poor community in the country, hundreds of millions of dollars are being invested by the Ethiopian Government, non-governmental organizations and Ethiopia's international development partners towards integrated landscape management, climate-smart land and ecosystem restoration and environmental protection. To enhance adoption, facilitate scaling, and increase efficiency (value for money) of these integrated efforts, it is essential to maximize the gains from land restoration and climate change adaptation/mitigation investments. Understanding climate and landscape function changes and their dynamics, and identifying "hotspots" of these changes is also critical for identifying gaps, bottlenecks and targeting priority areas for investment.

Analyzing the effects of climate change and land degradation requires long-term data. Unfortunately, consistent long-term in situ observation of climate forcing data are not available in most Sub-Sharan countries such as Ethiopia. Remote sensing data has an alternative advantage to overcome these shortfalls and provide consistent long term climatic data for comparative land surface dynamics investigation. The main objective of this study is, therefore, to investigate the effect of climate and land surface change on fresh water resources in Ethiopia using Budyko framework and remote sensing datasets. The specific objectives of the study include: (i) to analyze the impacts of climate and land surface change on the water cycle, (ii) to detangle the effects of climate variabilities and change, and land degradation on the hydrological water cycle, and (iii) to identify hotspot areas of climate and land surface changes in Ethiopia.

2. Study area

Ethiopia is located in the Horn of Africa with an area of 1,104, 300 sq. km. It is characterized by vast highlands and rugged topography, with 45% of mountain chains extending from central Southern to central Northern part of the country and dissected by East African Rift-Valley. The highlands are surrounded by the lowland and semi-desert areas placed along the borders. The largest lowland is found in the eastern and southeastern part of the country. In Ethiopia, elevation ranges from 116 meters below sea level in the northeastern Afar depression to approximately 4600 meters above sea level (mount Ras Dashin situated in Simien national park) (Figure 1). This varied elevation and topographic features of the country created diversified climate zones, soil types, and agro-ecological zones. The precipitation in is characterized by two main rainy seasons: the “Belg” period with brief bouts of rainfall (March - May) and the “Meher” period with long bouts of rainfall (June-September), the latter being the primary rainy season supporting 90-95% of the nation's total cereal grains production. Rainfall is highly variable in space and time, with annual rainfall 100 mm/year in the northeastern lowlands (Afar Depression) and 2500 mm/year in southwestern highlands of the Oromia Region. Variability in timing and amount of seasonal and annual rainfall is important factor for agricultural production. More information on climatic zones and rainfall pattern of Ethiopia can be obtained from Cheung et al. (2008). Rainfall distribution and its relationship with crop production in the country is also described in detail by Verdin et al. (2005). Land degradation is prevalent in the country affecting agricultural production and food security of the country due to the long history of anthropogenic interventions and population pressure, as well as the rugged topographic nature of the Ethiopian highlands. Among the SSA countries, Ethiopia experiences the most severe land degradation with an annual cost of $4.3 billion (Gebreselassie et al., 2016). A recent report shows that about 14.3 million ha of land in Ethiopia (about 50% of the highlands) is severely degraded due to deforestation, shifting cultivation, overgrazing, soil erosion, over cultivation, and land use conversion to croplands (Gashaw, 2015). Due to its severity and wide area coverage, land degradation in the country contributes to poverty with considerable negative impacts on the national economy (Gashaw, 2015).

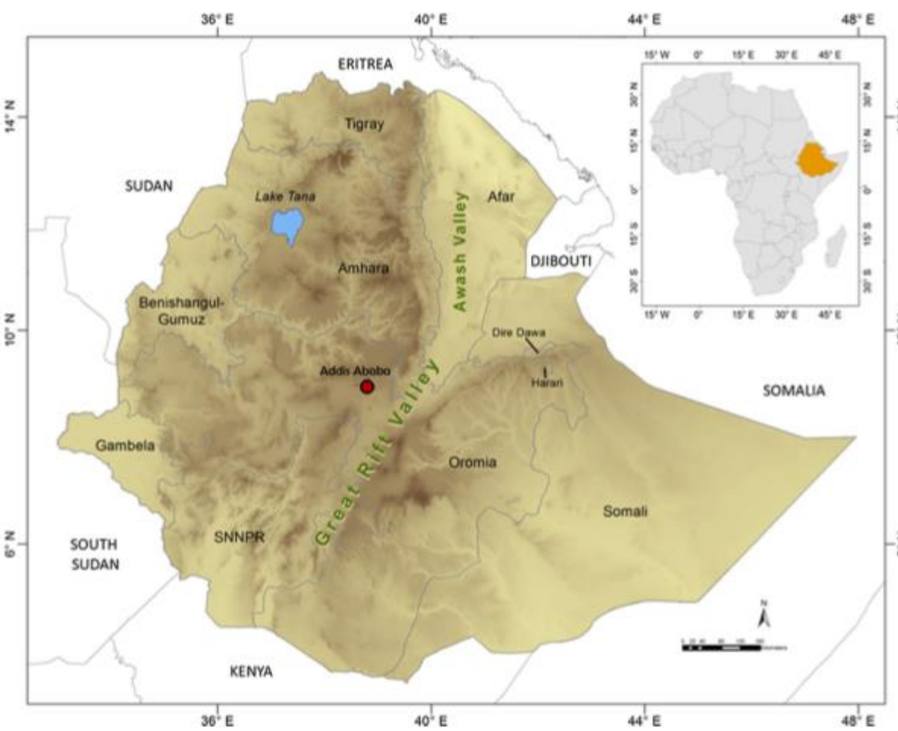

Figure 1: The location, topography, and administrative regional states of Ethiopia. The elevation ranges from 116 (light gray shades) to 4600 meters above sea level (darker brown shades) (Hermans-Neumann et al., 2017).

3. Methodology

In this section, we have presented: 1) the data set used, 2) methods for detecting the change in the hydrological cycle (landscape hydrological functioning), and 3) methods for separating the impacts of climate and land surface change on water resources.

3.1. Data

It is difficult to obtain long-term and standard *in-situ* observation/measurements of precipitation, river discharges, actual and potential evapotranspiration in Ethiopia. In selected situations or regions where such information is available (e.g. in the Upper Blue Nile basin), it is either highly sparse or inconsistent or that it lacks the required quality. In such situations, remote sensing (RS) data offers an alternative advantageous over *in-situ* observation for two reasons: i) RS can provide long period and consistent data that can be used for change detection, and ii) it is geospatially designated and can be available for all parts of the country. For applying Budyko framework and analyzing climate change and land surface change impacts on water resources, spatially distributed precipitation, actual and potential evapotranspiration are thus used from freely available and accessible RS products.

For this study, we used Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset (Beck et al., 2017). MSWEP dataset is a recently developed product which merges gauge, satellite, and reanalysis data, and has 3-hourly at 0.25deg globally gridded precipitation data set covering 1979-2015. It is assessed to be the best products and also performs higher than other satellite rainfall estimates in Africa. Detail procedures and development about MSWEP can be obtained from (Beck et al., 2017; Ciabatta et al. 2018).

Global Land Evaporation Amsterdam Methodology (GLEAM, version 3.b) (Miralles et al., 2011; Martens et al., 2017), a global, satellite-based, data set is used for both actual and potential evapotranspiration data. GLEAM uses Priestley-Taylor model (Priestley and Taylor, 1972) for estimating potential evapotranspiration (PET). GLEAM ET is assessed to be the best product available globally (Martens et al., 2017), and identified to be consistent with model ET in Upper Blue Nile basin (northwestern part of Ethiopia) (Abera et al., 2017). For any pixel, GLEAM actual evapotranspiration (ET) is obtained by multiplying GLEAM PET by "stress coefficient" which is parameterized for each land cover types (bare soil, snow, tall vegetation, two levels of low vegetation) based on soil moisture profile. All input data for evapotranspiration model including radiation and vegetation are used from different RS products (Martens et al., 2017).

For all data sets (precipitation (P), PET, ET), the native time steps are aggregated to yearly time series. A nearest-neighbor re-sampling algorithm is applied to P to synchronize with the GLEAM ET and PET spatial resolution to obtain the same resolution pixel for easy analysis of the water balance. To analyze the change and identify hotspots areas, we use two periods: 1990-1994 (now onwards Y1990 1994), and 2010-2014 (Y2010 2014). We used the 5-year average of P, ET, PET, with 20 years of interval (i.e. Period 1 and period 2), assuming that the mean obtained from the five consecutive years can represent both wet and dry years.

3.2. Budyko framework and metrics

While most of the Budyko-like frameworks are similar, here we used the most commonly applied one-parameter function framework, proposed by Fu (1981):

$$\frac{ET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{w}\right]^{(1/w)} \qquad (1)$$

Where P(mm), ET(mm), PET(mm) are the precipitation, actual evapotranspiration, and potential evapotranspiration. *w* is empirical parameter that determine the shape of Budyko curve and reflect the impact of landscape characteristics such as land use, vegetation and climate seasonality on water and energy balances (Li et al., 2013).

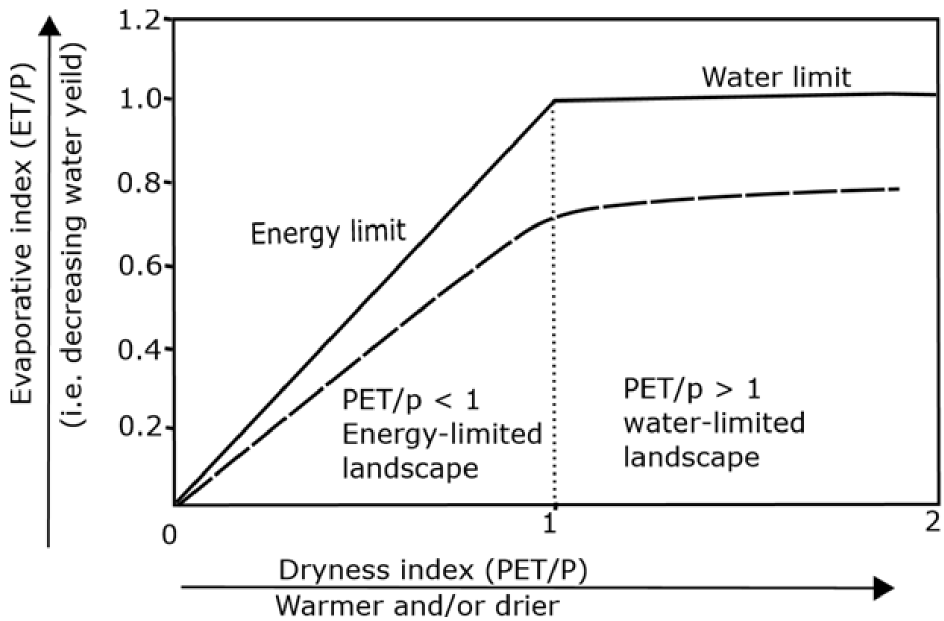

Figure 2: A Budyko diagram (evaporative vs. dryness index). The solid lines represent energy and water limits to the evaporative index, while the dashed line represents the original theoretical Budyko curve (after Budyko, 1974 and redrawn after Creed et al. 2014).

Budyko hypothesis denotes that various landscape characteristics co-evolve with climate so that the precipitation partition to each component follows the Budyko curve (Figure 2). However, recent studies show that significant deviation of water partitioning functions from the traditional Budyko curve, and thus the renewed Budyko applications are to understand the driving factors of these deviations. For instance, Xu et al. (2014), Zhang et al. (2008), and Li et al. (2010) used Budyko framework to analyze the sensitivity and contribution of P, PET, anthropogenic activities on discharge variability. Wang and Hejazi (2011), based on Budyko framework, developed a decomposition method to attribute discharge variability to various components. Xu (2011) also used Budyko-like framework to develop regression model and decompose the contribution of various human activities to the reduction of water resource in a basin. Comparative studies have shown that Budyko framework-derived methods are robust and effective in hydrological analysis (Zhan et al., 2014; Fernandez and Sayama, 2015).

In the current study, each landscape (pixel) is mapped on the Budyko space, as in Eq. 1, on its evaporative index (EI), which is defined as the ratio between actual evapotranspiration and precipitation (ET/P) and dryness index (DI), which is defined as the ratio between potential evapotranspiration and precipitation (PET/P) (Figure 2). If the pixels are distributed close to the theoretical Budyko curve, landscape water partitioning skill follows the Budyko function. The larger DI, the greater the proportion of precipitation that is partitioned to ET and less that is available for runoff and/or water yield. A landscape plotted at the left-hand side of the curve have greater water yield (and smaller EI) than that plotted on the right-hand side of the curve (larger EI) (Figure 2).

While the theoretical expression of the 5-year average annual water balance is partitioned as a function of EI and DI, the optimal *w* parameter is estimated for combined dataset for both periods using curve fitting procedures that minimize the mean square error between Budyko estimated EI and the observed ones, with the following objective function:

$$obj = \min \sum \left(\frac{ET_i}{P_i} - \left[1 + \left(\frac{PET_i}{P_i} \right)^{w} \right]^{1/w} \right) \quad (1)$$

where *i* is the 5-year average annual value for each pixel.

To assess the change in the long-term water partitioning characteristics of landscape (pixel), we compare the distribution of points in the Budyko space between Y1990 1994 to Y2010 2014. The distribution of pixels in Budyko space tells characteristics about the landscape regarding the water and energy balance. We used indexes to describe the potential departure from the theoretical Budyko curve of a catchments DI and EI points with time.

Deviation and elasticity (Creed et al., 2014) metrics were used to describe the departure of landscape position within Budyko space and from the theoretical Budyko curve of DI and EI between the two time periods. Deviation (d) is a measure of change in a landscape's EI relative to the Budyko curve as climate varies. It is used in the present study to explains how the allocation of precipitation to ET and runoff (Q) matches the theoretical expectations (BC) and provide information about the responsiveness (resistance) of a landscape for a given climate change. Low deviation means high resistance and responsiveness, and vice versa.

Elasticity index (e) is calculated as the ratio of ranges in water yield DI to the ranges in water yield EI residuals (EI_R). Mathematically, it is described as (Creed et al., 2014):

$$e = \frac{\left(DI_{\max} - DI_{\min}\right)}{EI_{R,\max} - EI_{R,\min}} \qquad (3)$$

where $EI_R = EI_m - EI_B$. EI_m is measured EI while EI_B is Budyko EI. A landscape (pixel) with high elasticity index means that P is partition into Q and ET in a way that produces a smaller change in EI_R values relative to the change in DI value, and therefore varies predictability with the Budyko curve. In other words, landscape with high e means the change in EI_R is more linearly related to the change in DI. On the other side, area with low elasticity index partitions water in less predictable manner.

3.3. Disentangling the contribution of climate and land surface change to water resources dynamics

To estimate the impact of climate and land surface changes on hydrological function, particularly on water availability, we re-wrote Eq. 1 to define it in terms of runoff (here it is defined the same as water yield) as follows (Roderick and Farquhar, 2011; Mwangi et al., 2016):

$$Q = P - ET = P - \left(1 - \frac{P \times PET}{\left(P^{w} + PET^{w}\right)^{1/w}}\right) \qquad (4)$$

The change in runoff (ΔQ) is expressed by the following total differential equation (Milly and Dunne, 2002; Roderick and Farquhar, 2011):

$$\Delta Q = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET + \frac{\partial Q}{\partial w}\Delta w \qquad (5)$$

where ΔQ, ΔET, ΔPET, and Δw are the changes in runoff, ET, PET, *w* respectively. Each term at the right-hand side of the Eq. 5 represents the contribution of runoff on P, PET and *w*, sequentially. Then the partial derivatives are given as follows:

$$\frac{\partial Q}{\partial P} = 1 - \frac{ET}{P}\left(\frac{PET^{w}}{P^{w} + PET^{w}}\right) \tag{6}$$

$$\frac{\partial Q}{\partial PET} = -\frac{ET}{PET}\left(\frac{P^{w}}{P^{w} + PET^{w}}\right) \tag{7}$$

$$\frac{\partial Q}{\partial w} = -\frac{ET}{P}\left(\frac{\ln(P^{w} + PET^{w})}{w} + \frac{P^{w}\ln P + PET^{w}\ln PET}{P^{w} + PET^{w}}\right) \tag{8}$$

Where the partial derivates are estimated using the 5-year average annual precipitation, actual evapotranspiration and potential evapotranspiration data of the two periods. The percentage contribution of each factor of Eq.5 can be given as follows:

$$\eta P = \frac{\frac{\partial Q}{\partial P}\Delta P}{\frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET + \frac{\partial Q}{\partial w}\Delta w} \times 100\% \tag{9}$$

$$\eta PET = \frac{\frac{\partial Q}{\partial PET}\Delta PET}{\frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET + \frac{\partial Q}{\partial w}\Delta w} \times 100\% \tag{10}$$

$$\eta w = \frac{\frac{\partial Q}{\partial w}\Delta w}{\frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET + \frac{\partial Q}{\partial w}\Delta w} \times 100\% \tag{11}$$

Where ηP, ηPET, ηw represent the contribution rate of precipitation, potential evapotranspiration and landscape characteristics to runoff variation, respectively, and where $\Delta Q = \eta P + \eta P\ ET + \eta w$. The contribution of climate and underlying land surface change to runoff can be estimated as follows:

$$\Delta Q = \Delta Q_{clim} + \Delta Q_{land} \tag{12}$$

Where

$$\Delta Q_{c\,\mathrm{lim}} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET \quad (13)$$

$$\Delta Q_{land} = \Delta Q - \Delta Q_{c\,\mathrm{lim}} \quad (14)$$

And the percentage contribution of the two can be given as:

$$\eta_{c\,\mathrm{lim}} = \frac{\Delta Q_{c\,\mathrm{lim}}}{|\Delta Q_{c\,\mathrm{lim}}| + |\Delta Q_{land}|} \times 100\% \quad (15)$$

$$\eta_{land} = \frac{\Delta Q_{land}}{|\Delta Q_{c\,\mathrm{lim}}| + |\Delta Q_{land}|} \times 100\% \quad (16)$$

Where ∆Q is the total runoff change, Q_{Clim} and Q_{land} are the climate induced and landscape surface induced changes, respectively, and η_{Clim} and η_{land} are the percentage contribution of climate and land surface change, respectively. To estimate the impacts of climate change and landscape change on water cycle, we used P, ET, and PET from two periods (Y1990 1994), and Y2010-2014). The first 5 year (Y1990-1994) mean annual P, ET, and PET are used to generate the Budyko curve. Then, the second 5 years (Y2010-2014) mean annual of the same climatic variable is used to generate the same Budyko curve. Then the change in each point from the first Y1990-1994to Y2010-2014 in Budyko curve space is partitioned into land surface and climate change components. To provide administrative, particularly zonal level, specific information, the mean zonal value is estimated by averaging all pixels within each zone of the country.

4. Results and Discussion

The results and discussion section is organized as follows: 1) plot and discuss DI and EI in Budyko space, fit Budyko curve based on optimal *w*, and map the spatial distribution of aridity index of the country during the two periods (Y1990-1994 and Y2010-2014); 2) present and discuss the changes in the landscape hydrological functioning using two Budyko metrics (i.e. deviation and elasticity) and map hotspot areas based on those matrices; and 3) present and discuss the contribution of climate change and landscape change on water availability.

4.1. The Budyko curve fitting for different periods

Figure 3 shows the distribution of 5-year DI and EI on Budyko space and fitting of three Budyko curves for three periods, i.e., 1st) for the period Y1990-1994; 2nd) for the period Y2010-2014; and 3rd) for the two periods combined. The distributions of observed data for the period Y1990-1994 and Y2010-2014 are shown in red and blue, respectively (Figure 3). According to this figure, comparison of the distributions of EI during the two periods show clear deviation in that the Y1990-1994 indicating proportionally higher EI in comparison to the Y2010-2014. Locations of scatter points around the Budyko line reflect the partitioning of P into ET and Q, and points above and below the curve exhibit relatively higher ET and Q, respectively. It is worth mentioning here the fact that some points are already out of the water limit (Li et al., 2013; Moussa and Lhomme, 2016). This is most likely due to availability of closed and lowland floodplain areas where runoff from highlands (upstream) might be added as an input to the water balance, while in the Budyko curve the only input to the water balance comes from precipitation. This distinction is very important in the case of Ethiopia, since there are many areas characterized by closed watershed (such as the ones at Awash and Hashenge basins, as well as at the floodplain of the Raya valley Graben. For instance, Meaza et al (2018) reported similar results that the input for Aba'ala graben (northeastern Ethiopia) is not just precipitation, but also runoff accumulation from graben escarpments. In addition, the occurrence of landscapes out of the Budyko's water and energy limit may be due to inaccurate estimation of input data (Jones et al., 2012). During Y1990-1994, the optimal *w* value was 3.4 which is relatively higher than the values reported by Chen et al. (2013), Donohue et al. (2012), and Xu et al. (2013), but still within the ranges of values reported in other studies (Li et al., 2013; Yang et al., 2009; Milly, 1994). However, for the period 2010-2014, we obtained lower value (w = 2.6), which is similar to the default value of the original Budyko index – as reported in the past by Zhang et al. (2004). The *w* value for the combined datasets of the two periods was 2.9. Variabilities of w (from 1.5 to 2.5) spatially between watersheds in the Upper Blue Nile basin was also reported (Tekleab et al, 2011). The higher *w* means higher ET for a given P and PET, hence lower runoff (Q) and vice versa. Here, the change of *w* from 3.4 to 2.6 (from period Y1990-1994 toY2010-2014), indicates that the landscape produced more Q for the given P and PET. The changes in the EI and DI of Y1990-1994 and Y2010-2014 do not follow the same Budyko curve, indicating changes in runoff might be most likely due to the prevailing changes in landscape properties.

Dryness index is by The United Nations Environmental program (UNEP,1992) to classify large swaths of landscapes, regions and ecosystems into Humid (DI < 1.5), Dry sub-humid (1.5 < DI < 2), Semiarid (2 < DI < 5), Arid (5 < DI < 20) and Hyper-arid (DI > 20) agro-ecological zones. Figure 4 shows the spatial distribution of dryness index of Ethiopia. According to the RS dataset and UNEP classification, the majority of the Ethiopian highland is clearly classified under the humid agro-ecological category, although some areas could fall under the dry-sub humid class. Large extent of the eastern part of the country is fall under the semi-arid and arid categories (Figure 4). According to the Budyko aridity index classification, areas with DI less than 1 are considered energy limited, and, in this case, the Upper Blue Nile basin (Figure 4 - inner part of the area designated in blue color) is energy limited while the rest of the country is characterized by water limited landscape. This agroecological zone is much coarser and smoother than FAO agroecological zone of Ethiopia, as the latter consider many factors such as temperature, landform, agricultural practices.

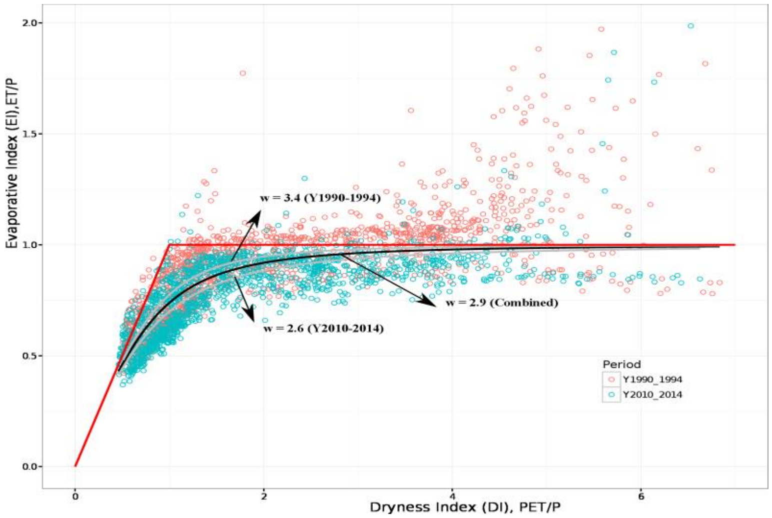

Figure 3: The 5-year average annual evaporative index (ET/P) in all pixel of the country plotted against the 5-year average annual dryness index (PET/P). The bold red curve represents the water and energy limit to the Budyko space. The two gray curves represent the Budyko curve for the periods Y1990-1994 and Y20102014. The bold black curve between the two gray curves shows the Budyko curve for the combined dataset.

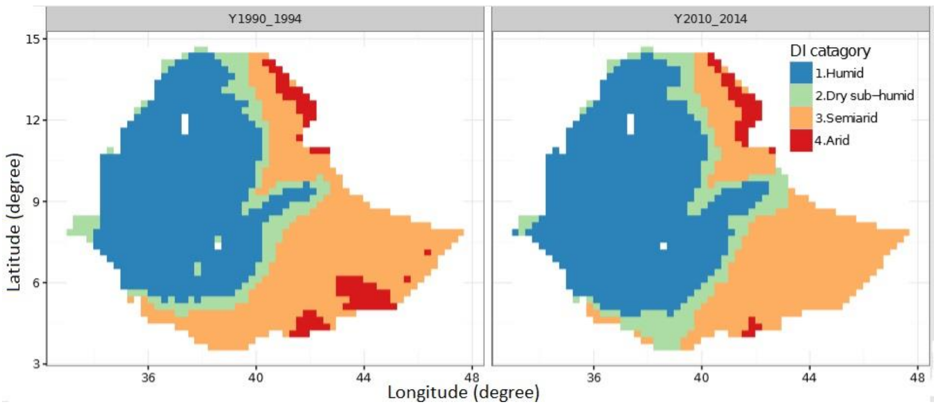

Figure 4: The spatial distribution of dryness index of Ethiopia according to UNEP classification during the two periods

4.2. Budyko based matrices: deviation and elasticity

We examined the change of EI and DI positions from period Y1990-1994 to period Y2010-2014, after 20 years using two indexes (deviation, *d* and elasticity, *e*). Figure 5a and b present the *d* and *e* of the landscape from Y1990-1994 to Y2010-2014, respectively. Deviation ranges from -0.4 to 2.0, and generally it is positive in most part of the country particularly in the southern half (Figure 5a), indicating that hydrological partitioning functions changes observed from Y1990-1994 to Y2010-2014, particularly decreasing water yield. Belihu et al. (2018), using 40 years of discharge measurement, supported the decreasing trend of streamflow in southern Ethiopia. In the northern central and northeastern parts of the country (represented by dark blue) shows negative d, indicating that the change in hydrological partitioning functions is towards increasing water yield. The areas with large changes are also shaded by red and light red in Figure 5a. Tesemma et al. (2010), using long term discharge measurement in the upper Blue Nile basin, confirmed this positive trend of water yield.

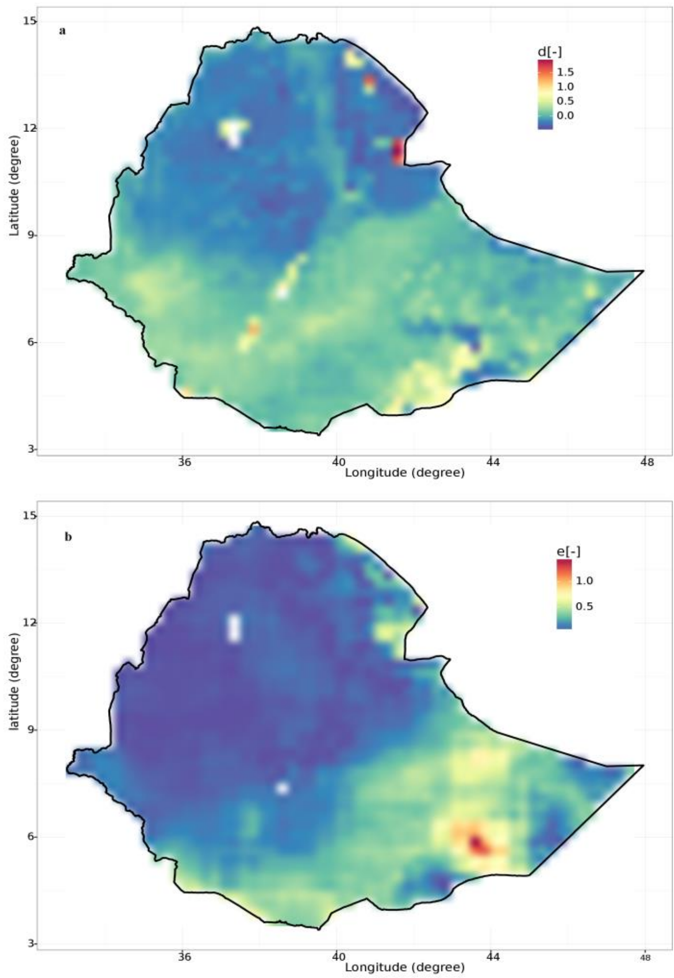

Figure 5: The spatial distributions of deviation (a) and elasticity (b) index values in Ethiopia.

Elasticity for Ethiopia ranges from 0.0 to 1.5. According to Figure 5b, most of the country (particularly the central and northern parts) is characterized by low *e* values *(<0.5)*, indicating that the water yield change is less predictable, and which also means that they are hydrologically less resilient (Figure 5b). On the other hand, the southeastern part of Ethiopia shows relatively higher e values (0.5 – 1.5), denoting that they are more resilient to change in DI, with their water yield changes more predictable than those in the northern highlands of Ethiopia. This shows that arid and semi-arid landscapes are more resilient and more predictable in water yield change than humid landscapes (Figures 4 and 5). Similar results are obtained by Helman et al. (2017) in the Mediterranean area. This is, however, independent of the water availability in the landscape, as it is rather based on the response to extreme event (changes). The high elasticity (high resilient behavior) attributed to dry-land areas could be because the relation between P, PET, and ET maintains to those found under average P condition, and helps to develop ecological adjustment of prevalent drought conditions to which the landscapes are frequently subjected (Maseyk et al., 2008; Baldocchi and Xu, 2007; Helman et al., 2017).

4.3. Contribution of climate change and landscape surface change on water availability

In this section, we analyzed the contribution of climate change and land surface change on water resource according to the Budyko framework. At national level, the 5-year mean annual runoff increased by 80 mm from period Y1990-1994 (150 mm/year) to period Y2010-2014 (230 mm/year). Figures 6 and 7 present the contribution of the two components. In both cases, negative values indicate that climate and land surface changes have contributed to declining water availability. At national level, the impacts of both climate and land surface change on water resource dynamics accounted almost equally (50% each, Figure 6). However, their contributions vary spatially as shown in Figure 6.

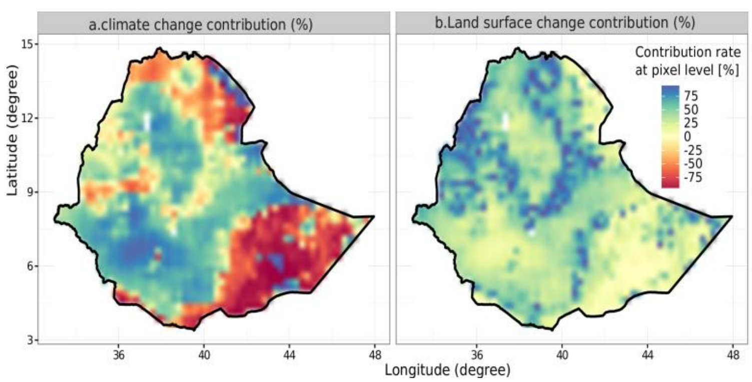

Figure 6: The spatial distribution of the contribution rate of climate and land surface changes on the available water resource in Ethiopia

Our result shows (Figure 6a and b) that climate change played larger negative role on surface water availability in the northern and the southeastern part of the country. According to Figure

6a, specifically in southeastern part of the country (Ethiopia's Somali region), about 70% of the change is attributed to climate change. A study by Taye et al. (2018), for Awash basin reported decreasing trend of water availability due to climate change – due particularly to a projected increase in temperature and a decrease in the precipitation. Our results show that regions around Upper Blue Nile basin portrayed that water availability is increased due to climate change. Roth et al. (2017) using various climate models confirmed that climate change will increase water availability in Upper Blue Nile basin by up to 97%. Dile et al. (2013) also forecast an increase in the flow volume of Gilgel Abay River in the Upper Blue Nile basin for future climate scenario. In addition, a case study in Werri watershed in Tigray region in Northern Ethiopia confirmed that runoff volume decreased by 13-14% due to climate variability and change (Gebremeskel and Kebede, 2018). In most areas, the contribution of landscape surface change is positive on water resource availability (Figure 6b). Based on Figure 6b, large positive contribution rate of landscape characteristics on surface water availability change is observed along the western side of the Rift-Valley escapements and at the western Upper Blue Nile basins of Ethiopia. Changes in landscape characteristics affecting water balance partitioning are highly related to the type and nature of vegetation change as indicated in some studies (Donohue et al., 2010, 2006; Stewart, 2013).

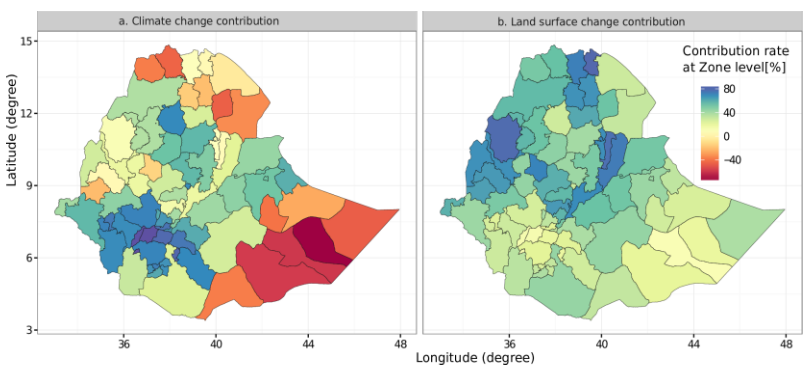

Figure 7: The same as 5, but aggregated at administrative zonal level. The name for each zone can be referred at the administrative map of Ethiopia.

The changes in climate and land surface properties exert opposite influences on a runoff could result minimal runoff change. For instance, landscape over Tigray (North part of Ethiopia) experiences significantly negative contribution on runoff (from -50 to -70%) due to climate change, but significant positive contribution (about 50 to 70%) due to changes in landscape properties (Figure 6a and b). This could be due to sustainable land management practices implemented to adapt climate change impacts, which in return resulted to an increase in available water in northern part of Ethiopia. Physical measures (e.g., bunds, trenches), and gully rehabilitation measures such as check dam and exclosures are commonly practiced in the region to enhance water infiltration and improve water availability (Mekonen and Tesfahunegn, 2011; Nyssen et al., 2008; Nyssen et al., 2010). However, soil and water conservation practices did not always contribute significantly to an increase in water availability in the upper part of Upper Blue Nile basin (Lemann et al., 2016). This implies that changes in landscape properties have minimal effect on water availability in the region while the opposite is true in southeastern Ethiopia. The zonal mean contribution is estimated by averaging all the pixels of climate change and landscape change data within each zone of the country.

5. Conclusions

Climate change and landscape characteristics are the two factors determining water resources. At large geographic and long temporal scale, Budyko-like framework and remote sensing data can be used to analyze water resource dynamics and to assess the contribution of climate and land surface change on surface water resources in Ethiopia. The deviation and elasticity indexes showed that nationally, the change in water resource is less, but they were able to also point out clearly spatial variabilities among the various geographical regions and landscapes. The southern and southeastern part of Ethiopia showed higher deviation and elasticity in comparison to the northern and western part of the country. The study shows that (i) at national level, the contribution of climate change and land surface change on water resource dynamics is almost 50% each, (ii) water availability is negatively affected by climate change in the eastern and northern part of Ethiopia, (iii) water resource is positively influenced by changes in landscape characteristics in the western part of Ethiopia and the western escarpment of Rift-Valley. On the basis of this study it is possible to conclude that both climate and land surface changes impact surface water resources in Ethiopia. It is also possible to suggest that hotspots mapping using large-scale geospatial and temporal Budyko framework and remote sensing data can be effectively used to gain deeper understanding of the hydrological cycles, water resource dynamics and to assess the contribution of climate variabilities and change, as well as the role of land surface and land-cover changes on water resources in a geographically and agro-ecologically diverse Sub-Sharan countries and landscapes such as the one in Ethiopia.

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