 doi:10.20944/preprints201908.0054.v1

Multi-Scale, Multi-Season, Multi-Indicator Evaluation of Agricultural Drought Trends in Ethiopia -Implications to Dryland Agriculture and Food Security

Dawd Temam[1], V. Uddameri[1,2,*], G. Mohammadi[2], E. A. Hernandez[2], S. Ekwaro-Osire[3,4]

[1] Department of Civil Engineering, Jimma Institute of Technology, University of Jimma, Jimma Ethiopia
[2] Department of Civil, Environmental and Construction Engineering, Texas Tech University, Lubbock, TX 79409, USA
[3] Department of Mechanical Engineering, Jimma Institute of Technology, University of Jimma, Jimma Ethiopia
[4] Department of Mechanical Engineering, Texas Tech University, Lubbock, TX 79409, USA
[*] Corresponding Author (email: venki.uddameri@ttu.edu; Ph: 806-834-8340)

Abstract:

Ethiopian agriculture is not only affected by precipitation declines (meteorological droughts) but also soil dryness caused by temperature increases and associated long-term hydrological changes. Meteorological drought indicators (e.g., SPI), do not fully capture the water deficits in agricultural systems (i.e., agricultural droughts). An Ethiopia-wide assessment of meteorological and agricultural drought trends was carried out to characterize century-scale (1902 – 2016) changes in droughts. SPI and SPEI calculated using two-month accumulation and the Palmer Z-index were used for assessing intra-season drought trends. SPI and SPEI at six-month accumulations and PDSI were used to define full season droughts. Detrended variance corrected Mann-Kendall test was used for trend analysis during Bega (dry), Belg (short-rainy) and Meher (long-rainy) seasons. The SPEI-2 and PDSI were most aggressive in characterizing intra-season and seasonal-drought trends. There is on average 1% - 6% annual increase in dryness with the lower estimate based on precipitation declines and the upper end accounting for seasonal soil moisture dynamics. The area between 37.5° E – 42.5° E denotes a climate hot-spot. Precipitation declines in Belg along the Ethiopia-South-Sudan/Sudan border during Belg and along Eretria-Ethiopia border during Meher have the potential to exacerbate transboundary water conflicts and further threaten the food security of the region.

Keywords: SPI, SPEI, PDSI, Palmer Z-index, Ethiopia, Food Security, Climate Change, droughts, Trend Analysis, Autocorrelation, droughts

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

Introduction

Ethiopia is predominantly rural with a large population dependent on agriculture and pastoral activities but there has been limited development of surface and groundwater resources (blue water) for irrigation [1]. Dryland farming is widely practiced in Ethiopia and accounts for over two-thirds of all agricultural land [2]. The nexus between rainfall and agriculture is so strong in Ethiopia that that the words drought and famine are often used interchangeably in the media [3]. Food security in rural Ethiopia is intimately tied to precipitation patterns. Droughts have frequently plagued Ethiopia and continue to be perceived as a major climate change threat affecting the long-term viability of rural livelihoods in the country [4,5].

Ethiopia is characterized by a high spatiotemporal rainfall variability [6] with as many as 14 different precipitation zones [7]. Precipitation exhibits a strong elevation dependency and is much greater in the highlands than lowlands, except perhaps in the west. Annual precipitation accumulations across the nation range from under 400 mm to over 2000 mm [8]. On an intra-annual basis, rainfall in Ethiopia exhibits a trimodal behavior. The main rainy season, (June – September) also known as *Kiremt* exists over all of Ethiopia except perhaps in southern and southeastern parts. The agricultural season corresponding with this rainfall is referred to as *Meher*. Both Meher and Kiremt are used interchangeably in local parlance and this practice will be adopted here as well. The country is generally dry during the months of October – January, except for the central part which receives some rainfall. This relatively dry period is locally referred to as *Bega*. The *Belg* is the shorter rainy season that extends from February – May but is the primary source of water in the southern and southeastern part of the nation [9].

The major crops in Ethiopia include a variety of grains (cereals), oilseeds and coffee [10]. Single season crops (wheat, teff and barley) are harvested during both Belg (5% - 10% of total production) and Meher (45% – 50% of total production). Long-cycle crops, (e.g., sorghum and maize) are grown over both the seasons (Belg and Meher) and account for nearly 50% of the total crop production [11]. The period between April – September/October represents the growing phase of the long-season crops. Pastoralists account for about 15% of the nation's population and depend on rainfall for healthy grasslands and water for their livestock throughout the year [12].

Understanding drought characteristics is essential for agricultural and livestock adaptations to climate change as well as sustainable water resources management in Ethiopia [5,13]. Several studies have been undertaken in recent years to evaluate precipitation trends and drought characteristics in various regions of Ethiopia [14,15]. The results from these trend analysis studies (summarized in Table 1) indicate several characteristics – 1) Most studies focus on a specific region and often employ datasets with less than 30 years of records, even national-scale studies are limited in the number of stations that are used due to long periods of missing records; 2) There is often significant intra-station variability even within a region (watershed) with some stations indicating trends while others showing no trends; 3) Mann-Kendall test typically without corrections for autocorrelation or linear regression are used to assess trends; 4) drought studies are predominantly focused on the standardized precipitation index (SPI) or meteorological droughts with a greater emphasis placed on higher accumulation periods (e.g., 12 months); 5) Declining precipitation trends are more consistently noted in south and southwestern portions of the country than in other parts of the nation.

Table 1: Major Hydroclimatic Trend Analysis Studies in Ethiopia

Study	Indicator	Region	Period	Findings	Approach
[9]	Rainfall	11 Key Stations across Ethiopia	1965-2002	Annual and Kiremt rainfall declines in Eastern, Southern and Southwestern Ethiopia	Original Mann Kendall Test
[16]	Rainfall extremes	11 Key Stations across Ethiopia	1965-2002	Extreme Seasonal Rainfall of Belg and Kiremt declined in Eastern, Southern and Southwestern Parts	Original Mann Kendall Test
[17]	Rainfall; Standardized Rainfall Anomaly	Amhara Region (12 stations)	Longest Period 1961-2003 but varies across stations	No Consistent pattern or trends in daily rainfall. Both increasing and decreasing trends were noted in the region	Correlograms; Regression and Sperman Rho (correlation coefficient)
[18]	Rainfall	13 Watersheds and 124 stations	1960-2002	Kiremet rainfall declines at a few gaging stations in Baro-Akobo, Omo-Ghibe, Rift Valley, and Southern Blue Nile Watersheds. However, no regional or watershed scale trends	Regression against time
[15]	SPI	Awash River Basin	30 stations with a maximum period of record of 1963-2003	SPI2 correlates well with streamflow (hydrologic droughts); Middle and Lower Awash Basin is more prone to droughts with comparison on SPI 12	Theory of runs and GIS mapping
[19]	Rainfall, Landcover and Streamflow	9 Weather Stations Upper Gilgil Abbey - Blue Nile Basin	1973- 2005	Statistically decreasing trend in rainfall for most months but increasing trends during most of Kiremt (June, July August)	Monthly Mann Kendall Test

Study	Indicator	Region	Period	Findings	Approach
[20]	Rainfall, Temperature	Ethiopia; Gaging stations	Mid 1970s - late 2000s	Belg and Kiremt rainfall has declined in parts of southern, south central, southwestern and southeastern Ethiopia. Temperature has increased over this time period	Kriging, Spatial Mapping and Trend analysis
[21]	SPI 3,4 6, 9, 12, 24 months	Ethiopia; GPCC gridded data (2.5º x 2.5º); ERA reanalysis products as well as 238 Gage Stations	1970- 2011	Precipitation Decline in Southern Ethiopia for both Belg and Kiremt; No trends in Central and Northern Parts	Regression against time; Bootstrap confidence Intervals
[22]	PDSI and PDSI-sc	Northern and Northwest parts of Ethiopia	1901-2014; CRU Data (0.5 x 0.5 grid)	Increase in temperature and characterization of drought frequencies	GIS Mapping and Visualization
[23]	Rainfall	12 Stations in Awash River Basin	Variable. Maximum Period of Record 1980 - 2012	No significant change in Belg but a decline in Kiremt Rainfall	Mann-Kendall and Sen Slope
[24]	Rainfall, Temperature and Agricultural Production	18 stations across Ethiopia	Variable Maximum Period of Record 1952-2015	No discerning trends overall in precipitation; Annual temperature has risen over the period	Exploratory analysis using charts and tables
[25]	Rainfall and Temperature; SPI and STARDEX Indices	87 - 120 weather stations across Ethiopia	1982-2012	No significant change in annual or bimodal (Belg and Kiremt rainfall); Increase in temperatures; Increase in rainfall intensity in most stations	Regression against time and GIS mapping
[26]	Rainfall and Temperature; PDSI	North Central Ethiopia (Woleka Sub-basin)	1901-2014	Annual, Kiremt and Belg rainfall has declined. Annual and Kiremt rainfall declines are statistically significant	Mann-Kendall with Autocorrelation

1

Trend studies are often noted to be contradictory or inconclusive and are known to depend upon regional divisions and the amount of quality data that are used to estimate trends [18,27]. In addition, the use of linear regression or traditional Mann-Kendall tests may not be appropriate in some instances due to the presence of autocorrelation in these datasets.

Meteorological droughts focus on the atmospheric moisture deficits and delineating their trends is undoubtedly important in Ethiopia given its high reliance on rainfed agricultural practices. However, the onset of an agricultural drought is typically marked by deficiencies in soil moisture [28] which is a complex function of precipitation as well as soil and land use characteristics of the watershed. The onset and cessation of agricultural droughts need not coincide with those of meteorological droughts. Antecedent soil moisture can help buffer the soil initially to withstand meteorological droughts. In a similar vein, soil dryness may continue to occur even after the cessation of meteorological droughts because of deep percolation and evapotranspiration. Therefore, trends in meteorological droughts may not translate to trends in agricultural droughts or vice-versa.

While soil moisture is regarded as the master variable to define agricultural droughts, the challenges in obtaining reliable soil moisture measurements greatly limits its use in drought studies. As plant water uptake is a function of temperature-controlled evapotranspiration, drought indicators that incorporate potential evapotranspiration (PET) are often used to characterize agricultural droughts [29]. In particular, the self-calibrating Palmer Drought Severity Index (PDSIsc) proposed by Wells et al. [30], and the associated Z-index [31] as well as the Standardized Precipitation Evapotranspiration index (SPEI) proposed by Vicente-Serrano et al. [32], have been

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

successfully used to characterize agricultural droughts in many parts of the world [33-35]. These indicators have however seen limited use in the Ethiopian context [22].

SPI, SPEI and PDSIsc are based on different physical aspects – SPI strictly focuses on precipitation which is controlled by global moisture movements and climate teleconnections; SPEI is based on a simple atmospheric water budget and PDSI (and therefore the Z-index) uses a two-bucket model for representing soil water budgets. As these drought indicators are based on different physical aspects and all have their own strengths and weaknesses, their ability to capture different drought characteristics may be different. It is therefore becoming a common practice to evaluate droughts using multiple indicators [36-38].

A simultaneous assessment of drought trends using multiple drought indicators is useful for drought planning and management studies. While some indicators may detect droughts in one season (say dry) another might exhibit greater sensitivity in a different (say wet) season. If various drought indicators (which are computed using different parameters and conceptualizations) all exhibit similar trends, then there will be greater confidence in the detected trend as all available information is pointing to the change. In such an instance, the use of a simpler drought index (e.g., one based on precipitation alone) would be validated and deemed reasonable for trend detection. If different drought indices exhibit diverging trends, then additional insights with regards to the underlying mechanisms driving droughts can be ascertained [39]. For example, if SPI exhibits no trend but SPEI indicates an increasing drought trend then drying of soil moisture due to increased temperatures (as opposed to precipitation deficits) is likely the dominant mechanism controlling

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

agricultural droughts. Identification of such underlying factors are helpful to guide future data collection activities and identify mechanistic shifts in drought producing processes [40].

The primary goal of the present study is to undertake a multi-indicator evaluation of agricultural drought trends in Ethiopia. The study evaluates trends of drought severity for *Bega*, *Belg* and *Meher (Kiremt)* seasons using four major drought indicators namely – SPI, SPEI and PDSIsc (referred to as PDSI from here on for brevity) and Palmer Z-index (referred to as Z-index hereon). A simultaneous comparison of drought trends from multiple indicators is an important knowledge gap in Ethiopian context that this study seeks to address. In addition, the study also aims to overcome some other limitations identified in previous studies such as assessing trends using high resolution spatio-temporal datasets and choosing techniques that appropriately deal with the nature and extent of autocorrelation present in hydrometeorological datasets.

Datasets and Methods

Following Asfaw et al. [26], GPCC Full Data Monthly Product Version 2018 from Global Precipitation and Climatology Center (GPCC) available on 0.5^o x 0.5^o grid [41] were used along with temperature data from Climate Research Unit (CRU TS 4.21) as described in Harris et al. [42]. GPCC Full Data Monthly Product is the most comprehensive gridded precipitation dataset available today and is based on measurements from over 80,000 stations worldwide. When this study was conducted, the dataset covered a period ranging from January 1891 – December 2016 [38, 43]. While GPCC data are available at different spatial resolutions, the data with 0.5^o x 0.5^o spatial resolution was used to be consistent with the resolution of the available temperature data.

The precipitation data at the adopted resolution is known to provide reasonable estimates in Ethiopia [26].

The CRU Climate Dataset is produced by the Climate Research Unit at the University of East Anglia and is also gridded at a resolution of 0.5^o x 0.5^o over the land mass and during the time of this study, data were available at a monthly time-step from 1901-2017. The CRU dataset is again based on long-term observations from several thousand stations worldwide that are compiled under the auspices of World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA through its National Climate Data Center, NCDC). This dataset has also been used in several hundred climate change assessment studies and known to provide reasonable estimates for temperature [42].

The adopted spatial resolution (0.5^o x 0.5^o) resulted in 377 locations wherein the nearest neighbors are approximately 50 km apart (see Figure 1a). The 15 major water basins in Ethiopia are shown in Figure 1b and represent the federal level water planning boundaries of the nation. Figure 1c shows the land use land cover (LULC) classification which highlights the rural nature of the country with high reliance on climate-dependent agricultural and pastoral activities. As depicted in Figure (1d), Ethiopia exhibits a great variation in relief ranging from areas below mean sea level to mountain ranges that are over 4000 m high, Precipitation correlates strongly with elevation with higher elevations getting more rainfall than lowlands.

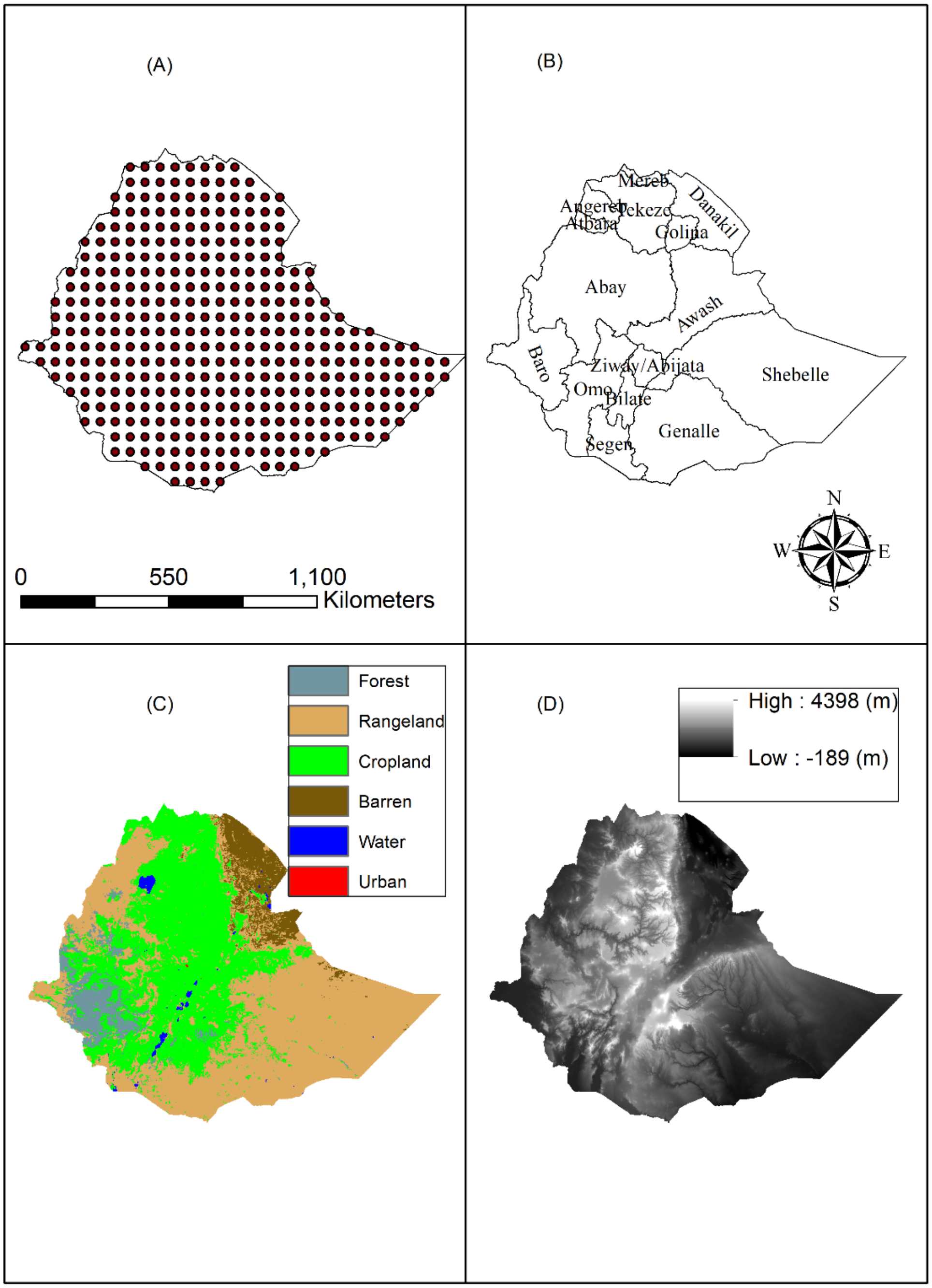

Figure 1: Study Grid and Geographical Characteristics of Ethiopa

Four drought indicators – SPI, SPEI, PDSI and Z-Index were used to assess droughts. The SPI and SPEI calculations were carried out using procedures presented in Stagge et al. [44], to correct for zero precipitation values that are likely during dry months. As the study focuses on agricultural droughts SPI and SPEI were computed at 2-, 3-, 4- and 6- month accumulations to evaluate both intra-seasonal and full season trends. The analysis indicated that the results of intermediate accumulation periods (3- and 4-months) yielded results that were similar to the bracketing accumulation periods of 2- and 6-months. As such, the results are only presented here for 2-month (intra-season) and 6-month (full-season) accumulations in the interest of brevity. The Z-Index represents short-term (monthly) soil moisture dynamics as it factors out the long-term effects embedded within PDSI [31,45]. Studies have indicated that PDSI does a better job of predicting longer-term droughts [32] and is seen to correlate well with SPI and SPEI values computed using higher accumulation periods [46]. Therefore SPI-2, SPEI-2 and Z-Index are used to characterize intra-season or short-term droughts while SPI-6, SPEI-6 and PDSI are used as indicators of full-season or long-term droughts.

The drought indicators were all computed on a monthly basis and then aggregated to obtain values for seasonal climate states. For a hydrologic year, the seasons were defined as *Bega* (October-January); *Belg* (February – May) and *Meher* (June – September). Trend analysis was carried out over hydrologic years 1902 – 2016 (Oct. 1901 – Sep. 2016) and to the best of the authors' knowledge this represents the longest assessment period in Ethiopia that has been documented in the literature. Century-scale trend assessment studies, such as the one conducted here, better capture a higher degree of climate variability than what is observed at shorter timespans which in turn helps minimize artifacts associated with any short-term or cyclical effects present in the climate signals.

Exploratory data analysis indicated the presence of autocorrelation even when drought indicators were aggregated over the season to create an annual time-series. Furthermore, autocorrelation structures that were observed varied across indicators and in space (see Figure 2 for an illustrative example). In all cases, at least the lag-1 autocorrelation was significant. Autocorrelation effects from higher-order lags were also significant and had to be corrected for at several locations. Many approaches have been suggested in the literature to properly assess trends in autocorrelated time-series [47-50]. The detrended variance correction approach of Yue and Wang [50] was adopted here because it has lower false detections than rank-based variance corrections methods [48,50]; is known for its ability to deal with higher order dependencies [51] and has statistical power comparable to more computationally intensive block bootstrap methods [52]. Custom scripts were developed in R software [53] that made use of available libraries and packages for pre-processing data [54] calculating drought indicators [55,56] and performing variance corrected Mann Kendall tests [57].

 doi:10.20944/preprints201908.0054.v1

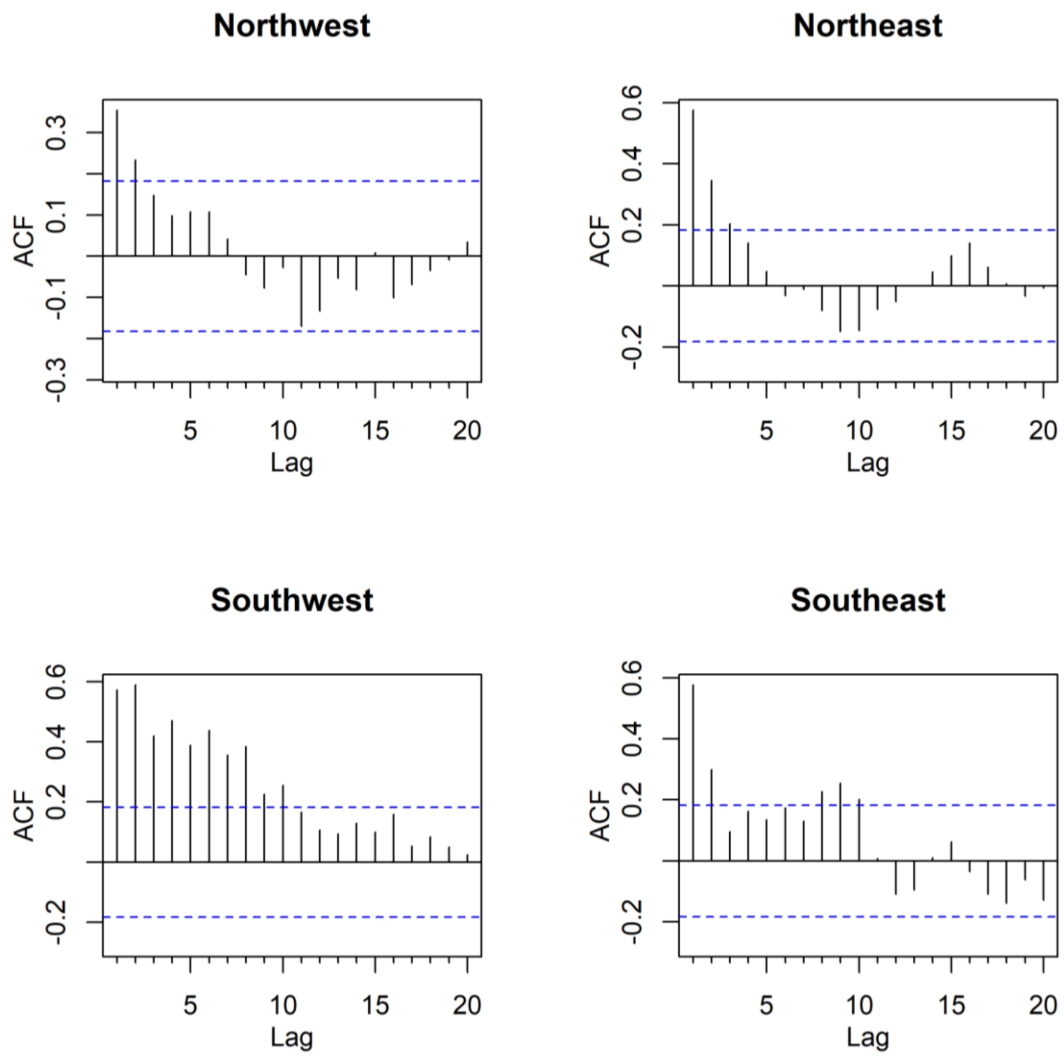

Figure 2: Illustrative Autocorrelation Functions Noted at Different Locations in Ethiopia for PDSI

Indicators used in this study specify droughts with negative values (below a threshold) and wet periods using positive values (above a threshold). As trend analysis was carried out using the seasonally aggregated sum of the drought indicator, a negative trend implied the drought indicator became more negative (or less positive) over time (i.e., increase in drought severity or a drying trend) while a positive trend implied a shift towards more positive (or less negative) value over time (decrease in drought severity or a wetting trend).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

Results and Discussion

Trends across Ethiopia during Bega Season:

The Bega season (October – January) has the lowest rainfall amounts compared to other seasons within the year (~ 2% of the annual precipitation of the country). Nonetheless, rainfall during Bega is important for several reasons. Bega rains can be significant in the central portions of the country. Bega rains provide much needed antecedent soil moisture that facilitates the tilling and planting of Belg crops. Bega rains are also important to maintain grasses in rangelands that pastoralists depend upon throughout the year. Therefore, declines in Bega rainfall can have devastating impacts in both agricultural and pastoral activities of the nation.

Figure 3 depicts the century-scale drought trends during the Bega season across Ethiopia. The left panel depicts short-term (intra-season) drought trends captured using SPI-2, SPEI-2 and Z-index while the right panel depicts full season effects captured using SPI-6, SPEI-6 and PDSI. Declines in precipitation (increased meteorological droughts) can be seen in southeastern and northwestern portion of the country. Decreased meteorological drought intensities or increased precipitation can be at some locations in the east. Null hypothesis of no drought trend could not be rejected over much of the southwestern and northeastern as well as western portions of the nation. Bega rains are critical in the central portions of Ethiopia and the short-term rainfall has either not changed or increased in the west-central portions while statistically significant (0.05 significance level) declining trends can be seen in the east-central sections of the country.

 doi:10.20944/preprints201908.0054.v1

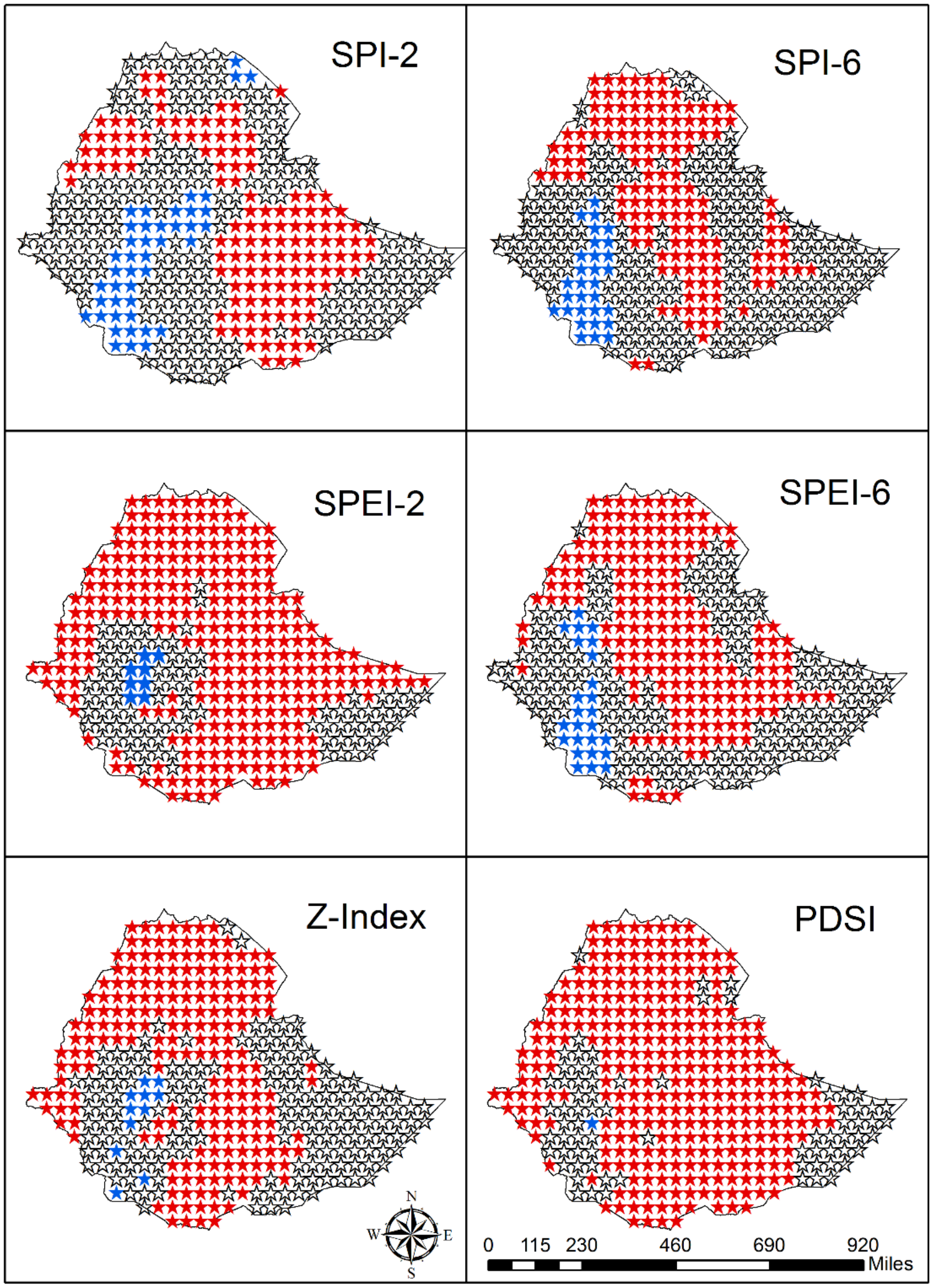

Figure 3: Observed Trends in Bega Drought Indicators (Red: Drying Trend, Blue: Wetting Trend and Black – No statistical trend)

Many locations that have a wetting SPI-2 trend either have no or exhibit drying trends for SPI-6 which accumulates more of Meher and Belg rainfall. This result appears to indicate that some of the noted increased wetness could be attributable to shifts in precipitation patterns. In a similar vein, there are greater number of wetting trends noted with SPEI-6 than SPEI-2. This result points to likely warming in the winter months (Oct-Jan) which is dampened over a longer-accumulation periods. The PDSI is the most aggressive indicator in terms of predicting long-term agricultural droughts. While Z-index does not point to significant wetting trends, it is unable to discern negative trends in the southeastern portions of the country. SPEI-2 appears to exhibit slightly better statistical power in discerning short-term agricultural droughts in this region season.

The magnitude of the observed trend is important to evaluate the rate of progression of observed wetting and drying phenomena. Figure 4 depicts the Sen's slope values for different drought indictors for Bega season. The Sen slope was set to zero when the null hypothesis of no trend could not be rejected. Figure 4 shows that the median magnitude of the Sen's slope was ~0.005 drought units (DU) /y for SPI-2 and ~ 0.01 (DU/y) for SPEI-2 and Z-Index. At least 75% of the locations exhibited a drying precipitation trend and this number increases considerably for SPEI-2. While Z-index is not aggressive as as SPEI-2 in identifying drying trends, the rate of drying for Z-index exhibits a much larger variability and sometimes more intense then SPEI-2. The results suggest precipitation-induced dryness is increasing at a rate of 5% per decade while agricultural droughts are intensifying at a rate of 10% per decade. This implies temperature increases (global warming) on average doubles the intensity of precipitation declines for short-term droughts during Bega.

 doi:10.20944/preprints201908.0054.v1

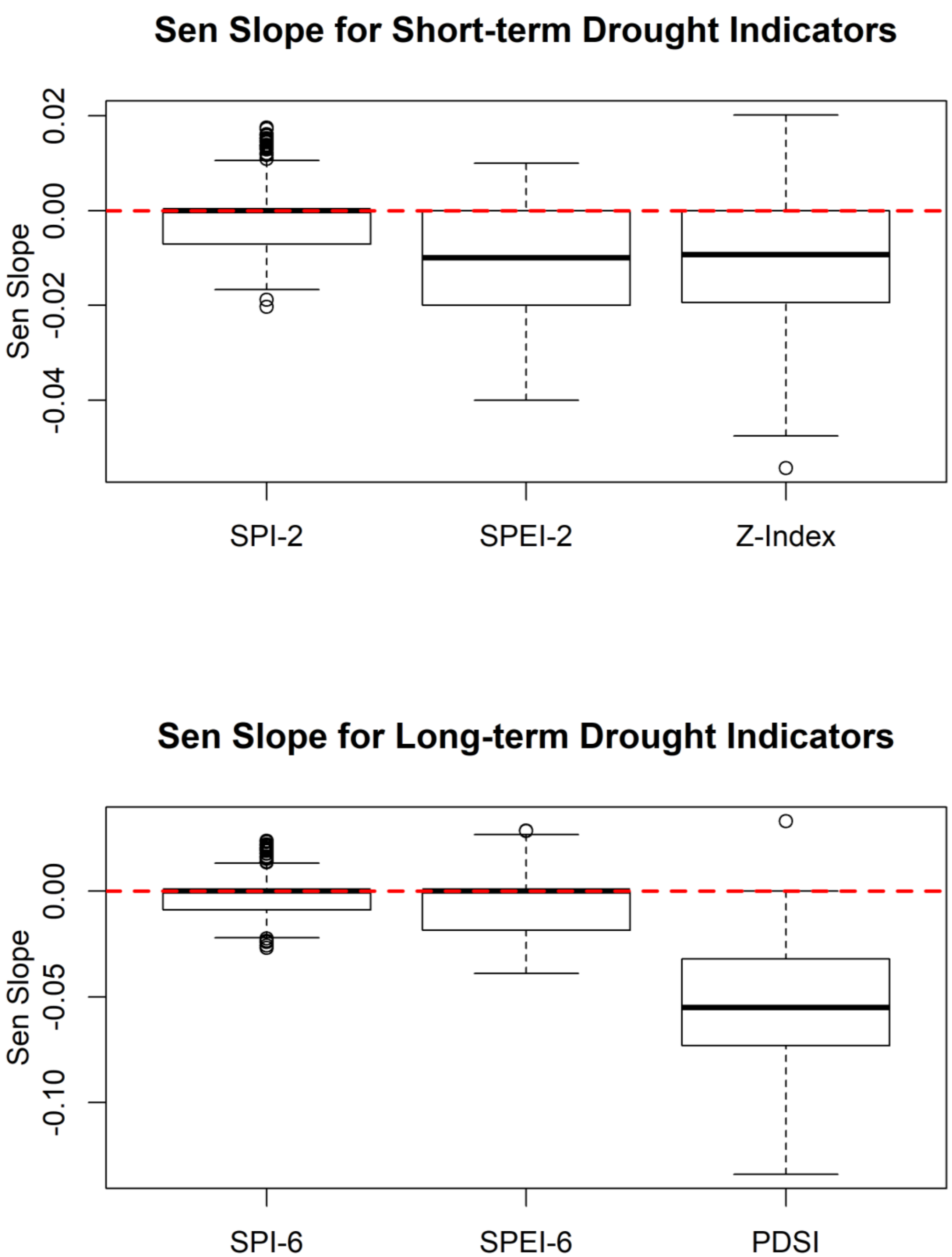

Figure 4: Variability of Sen's Slope for Various Indicators for Bega Season

The long-term wetting and drying trends produce a vastly different picture than short-term drying effects. The median precipitation related drying intensity is much smaller ~0.001 DU/y, for SPI-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

6 and only slightly higher for SPEI-2. PDSI on the other hand exhibits a strong drying intensity of ~0.05 DU/y (5% increase in dryness per year). This result indicates that while surficial dryness arising due to increased atmospheric temperature may not be significant (SPEI-6) it does have a considerable effect on the hydrologic soil water balance as conceptualized and computed by PDSI. The long-term PDSI trends are occurring at an alarming rate. Accurate soil moisture measurements are critical to rigorously validate the trend projections of PDSI.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

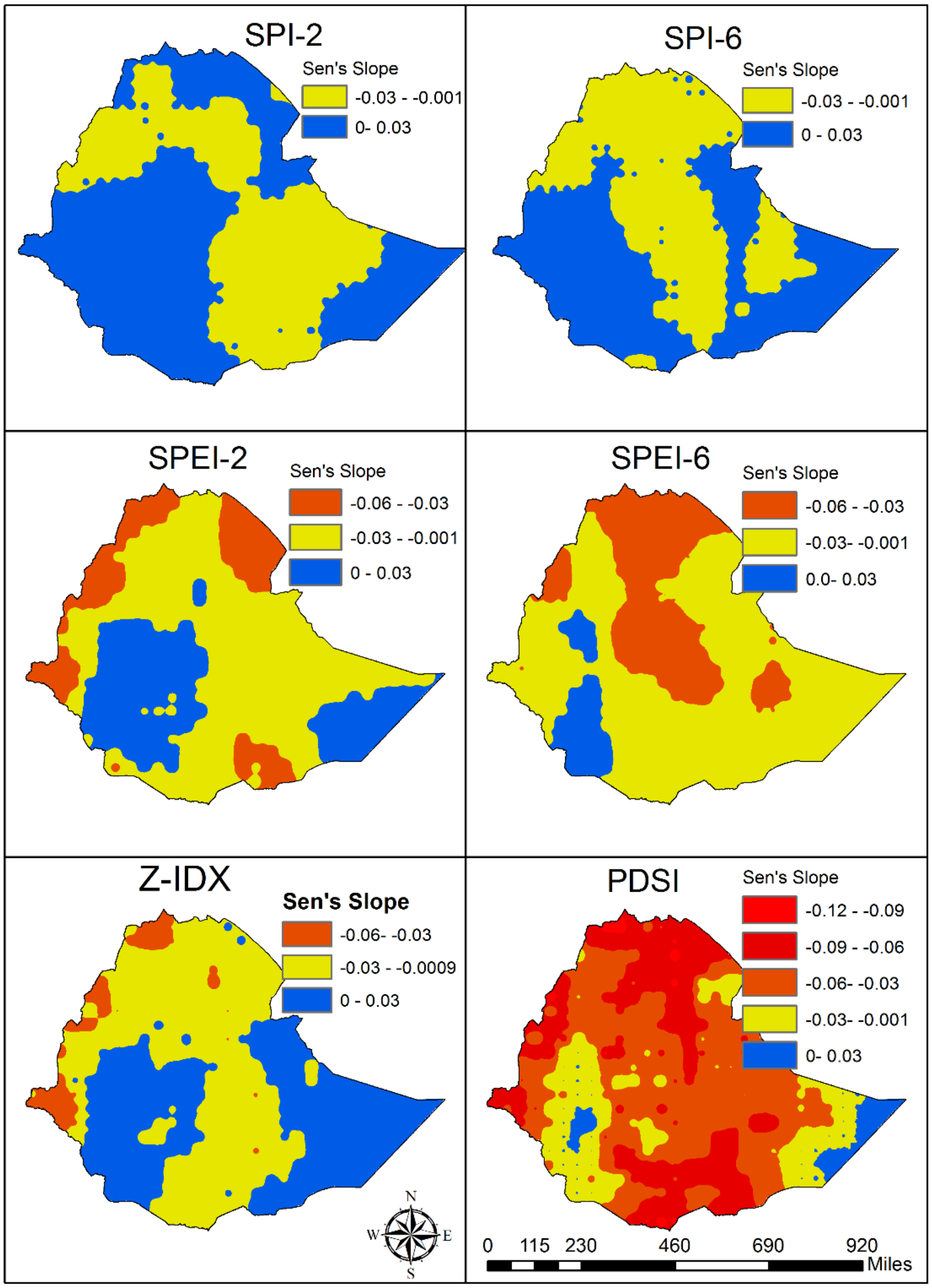

Figure 5: Variability of Sen's Slope Across Ethiopia for Various Drought Indicators for Bega Season

As to be expected, the magnitudes of wetting and drying trends also exhibit considerable spatial variability. The north and north-central portions of the country are experiencing highest rate of drying intensity compared to eastern and western portions of the country. Short-term Bega

 doi:10.20944/preprints201908.0054.v1

precipitation deficits (as denoted by SPI-2) appear to transition from a wetting to a drying trend moving west to east across the Rift Valley. It can also be seen that the trend variability is not uniform across the indicators with PDSI and Z-index showing much different trends than SPI and SPEI based indicators. This result highlights the fact that a single indicator does not provide the complete picture of the droughts during Bega.

Trends across Ethiopia during Belg Season:

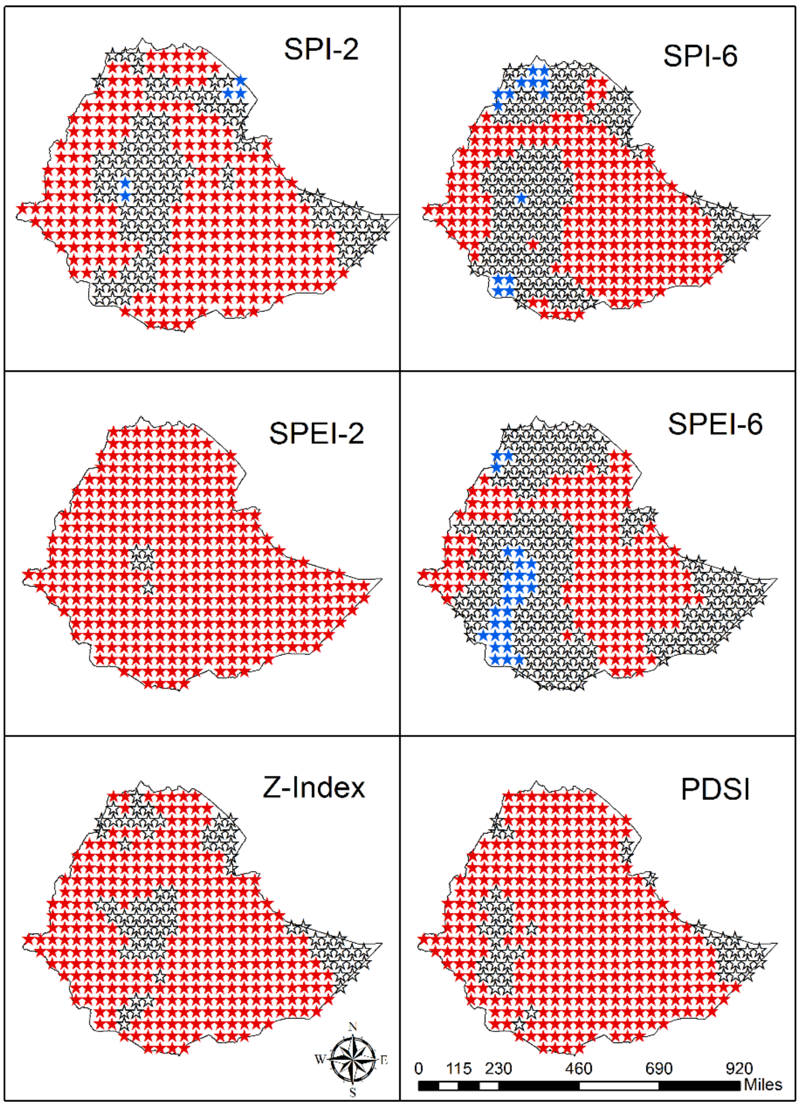

Figure 6: Trends for Various Drought Indicators Across Ethiopia for Belg Season (Red: Drying Trends and Blue: Wetting Trends, Black: No Trends

Figure 6 indicates that drying trends are most prevalent during Belg season especially in-comparison to the Bega season (Figure 4). Belg rainfall result from easterly and southeasterly winds which bring considerable rainfall to eastern and southeastern parts of the country. Barring SPEI-6, none of the other agricultural drought indicators predict wetting trends. Again, for short-term droughts, SPEI-2 provides the most aggressive trend detection (mostly drying trends) compared to SPI-2 and Z-index. On the other hand, PDSI predicts drying trends over a much larger spatial extent than other long-term drought trend indicators (SPI-6 and SPEI-6) highlighting the important role of long-term hydrological processes in defining agricultural drought trends.

A comparison of SPI-2 and SPEI-2 indicates that many areas where SPI-2 (precipitation) had discerned no trend appear to show declining trends under SPEI-2 indicating that increased temperatures is likely an important mechanism for controlling intra-seasonal droughts. However, as declining SPI-2 (precipitation) trends can be seen across Ethiopia, precipitation declines during this season also exert a considerable amount of influence on short-term agricultural droughts. The SPEI-6 shows lesser drying trends and even some wetting trends compared to SPI-6 this result indicates that SPEI-6 carries over the effects of Belg and Mehir more so than SPI-6. The small section in the northern portion where SPI-6 shows wetting trend is masked by temperature effect of SPEI (resulting in no SPEI-6 trends in that area). However, some areas where precipitation has not changed (no trends in SPI) are marked as positive (wetting) trends by SPEI-6, especially in the south and south-central portions of Ethiopia. This result points to a likely cooling effect (during Belg and late Mehir seasons likely due to increased humidity and cloud cover) in these portions of the country which SPEI-6 is able to capture in terms of reduced PET. As, with Belg (Figure 3) the Z-index and PDSI exhibit drought patterns that are considerably different from SPI and SPEI.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

While Z-index may be somewhat buffered by soil moisture storage in some pockets of the country (where no trends are detected), the PDSI trends indicate that this storage is short-lived and not sustained over the entire growing season due to the effects of hydrological processes that remove water from the soil column.

Belg season is important for growing Tef (*Eragrostis Tef*) which is a staple food and empirical evidence of farmers unable to harvest their crops during this season has been discussed by Rossel and Holmer [58]. As Tef grown during Belg is mostly consumed internally, agricultural droughts during Belg has profound implications to the food security and livelihoods of Ethiopia. Furthermore, if the production of Tef is shifted to the longer Mehir season, the growth of high valued (export-oriented) crops comes under threat affecting the economic viability of the nation which depends extensively on agricultural production.

The Sen's slope values are much higher in magnitude when compared to Bega season. The median drop rate is ~ 0.01 DU/y for SPI-2, ~ 0.03 DU/y for SPEI-2 and ~0.02 DU/y for Z-index. At these historical rates, the intra-seasonal drought indicators are changing (declining) on average) by 10% - 30% over a decade. In a similar manner the changes in SPI-6 (~0.01 DU/y), SPEI-6 (~0.00 DU/y) and PDSI ~0.06 (DU/y). The median changes in short-term and long-term SPI are roughly the same, there is an improvement in SPEI, and PDSI changes are most drastic over all indicators. The declines in precipitation during Belg, especially in relation to Bega stands out and the declines in precipitation plays a much greater role in defining agricultural droughts in this season.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

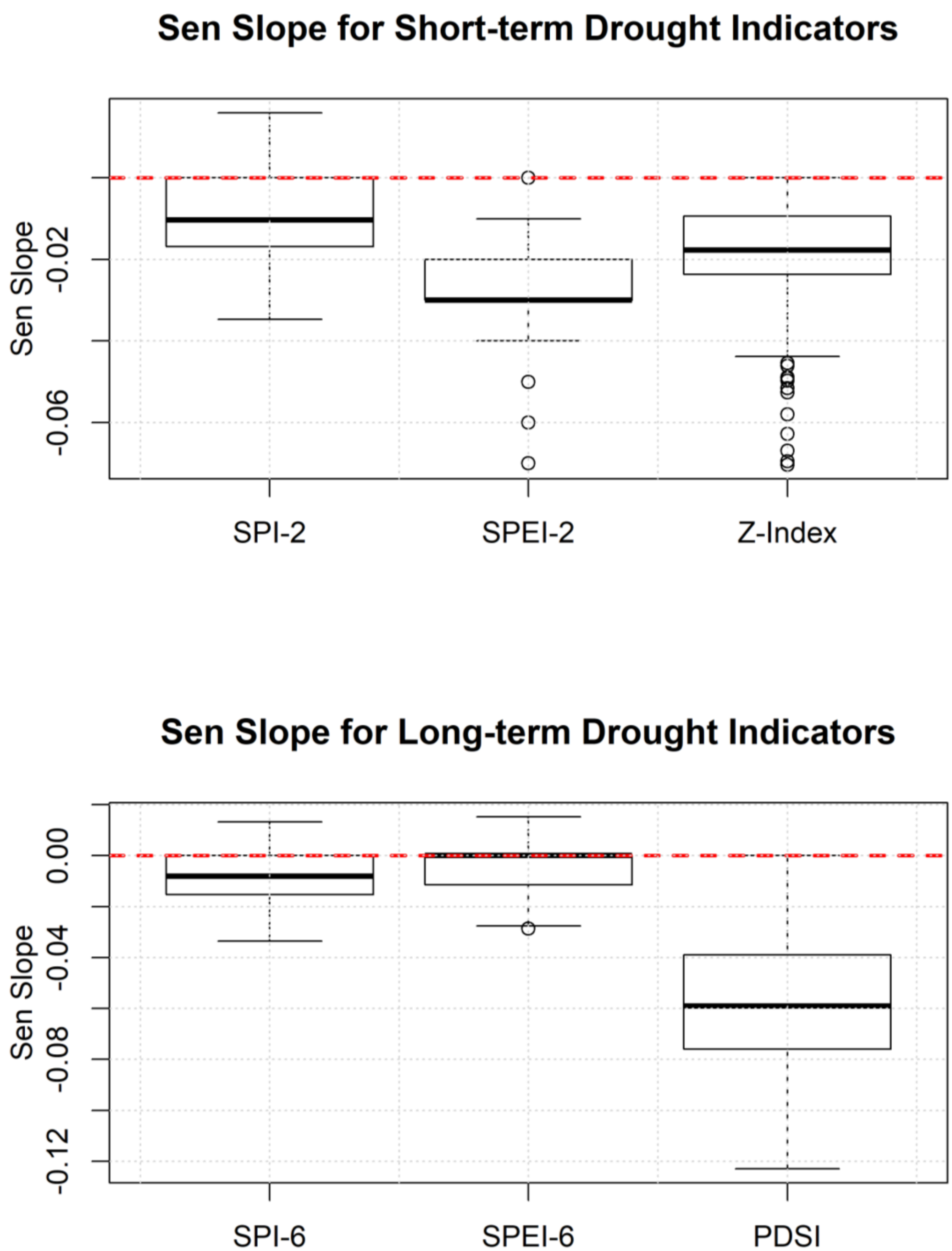

Figure 7: Variability in Sen's Slope for Various Drought Indicators Across Ethiopia during Belg Season (Sen Slope was set zero when there was no trend detected)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

The variability of Sen's slope for various drought indicators during Belg season is shown in Figure 8. Areas along the eastern border (Sudan and South Sudan) are generally seeing increased dryness in both short-term and long-term trends. This drying along the Sudan border will likely exacerbate already existing water resources conflicts, especially the sharing of transboundary rivers such as Blue Nile between Ethiopia and her neighbors. Increased dryness can be seen across the east central portions again across all indicators, albeit with different intensities. This area includes cities such as Dira Dawa and Dolo Odo which are critical for the development of eastern Ethiopia. All in all, both meteorological and agricultural droughts have increased over the last century. This declining trend in conjunction with a rapidly increasing population and limited irrigation systems has profound implications on the future food security of the nation and highlights the need for improved irrigation systems to build resilience into Ethiopian agricultural systems.

 doi:10.20944/preprints201908.0054.v1

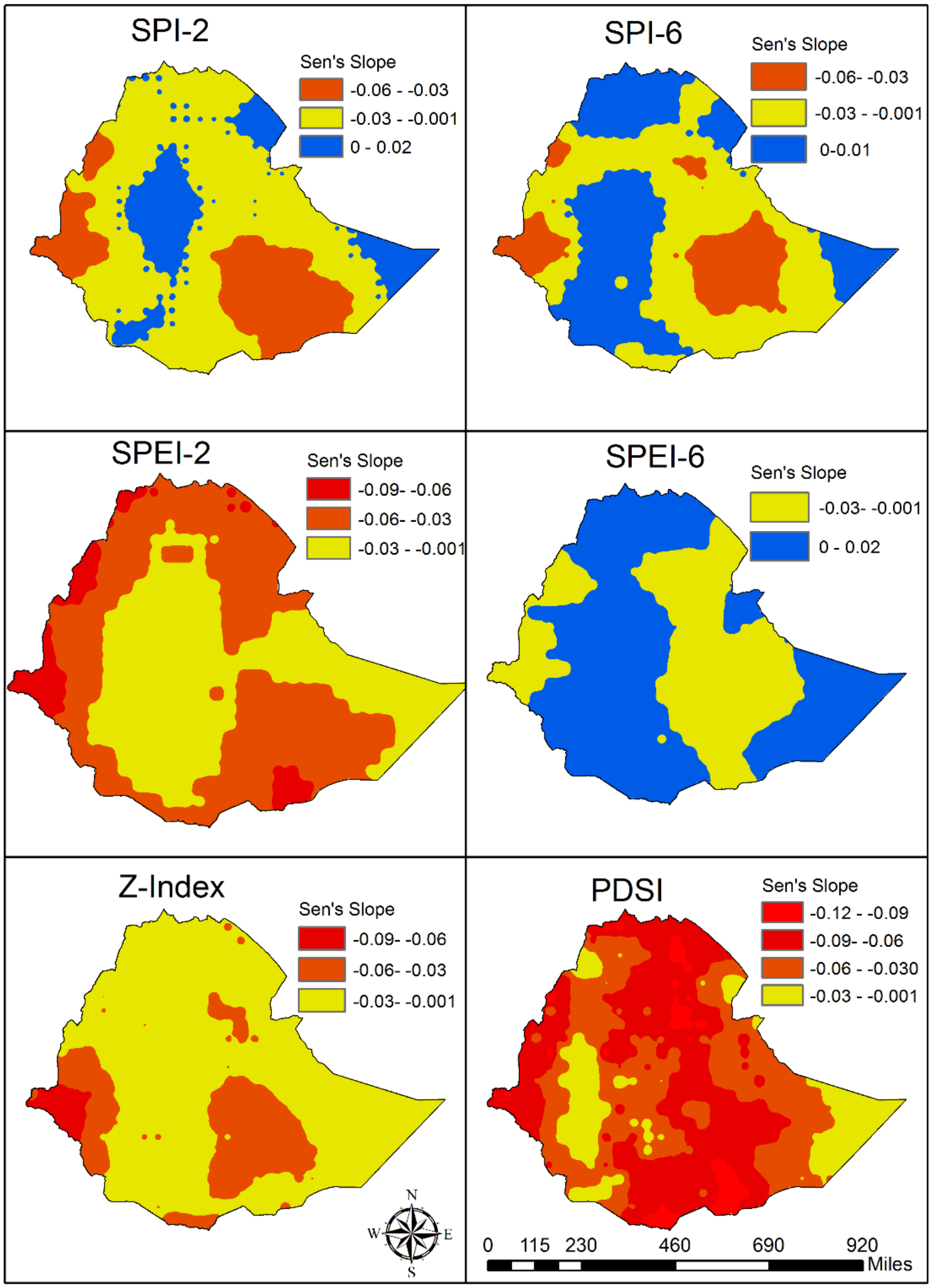

Figure 8: Variation in Sen's Slope Across Ethiopia for Various Drought Indicators for Belg Season

doi:10.20944/preprints201908.0054.v1

Trends across Ethiopia during Meher Season:

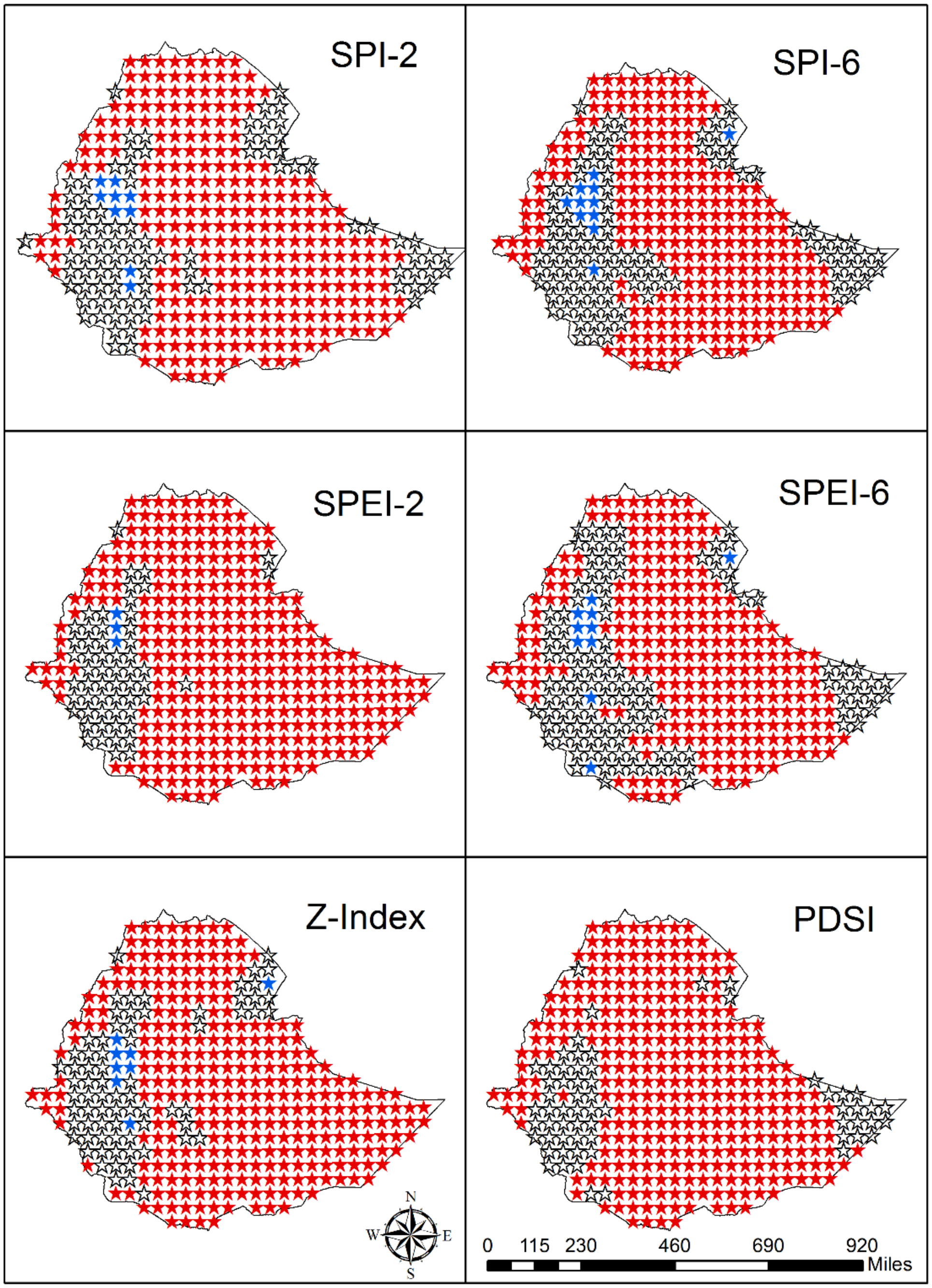

Figure 9: Trends Across Ethiopia during Meher Season for various Drought Indicators

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

Rainfall during Meher season is caused by the convergence of low-pressure systems and the inter tropical convergence zone (ITCZ). This is the main rainy season across most of the Ethiopia where majority of crops are grown. Figure 9 shows the trends of various drought indictors across Ethiopia during Meher season. Again, significant drying trends both due to precipitation declines as well as warming can be seen over large parts of the country. A few locations do exhibit increasing rainfall trends (see SPI maps) which is dwarfed by changes in temperature (see SPEI maps). Warming effects can be noticed both in short-term and long-term drought indicators. Again, SPEI-2 is the most aggressive of all short-term drought indicators while PDSI exhibits greatest sensitivity to predicting long-term droughts. As rainfall during this season is mainly derived from ITCZ, the narrowing of ITCZ noted over the last century [59] could perhaps explain some of the noted increased dryness. Seleshi and Zanke [9] also indicate that warm El Niño–southern oscillation episodes correlate well with declines in June–September rainfall over the Ethiopian Highlands.

The magnitude of median Sen's slope is ~0.018 DU/y for SPI-2 and around 0.02 DU/y for SPEI-2 and Z-index indicating that temperature changes due to global warming exacerbate the dryness induced by precipitation declines for most part of Ethiopia (Figure 10). For long-term droughts, SPI-6 and SPEI-6 have a median Sen's slope of ~ 0.01 DU/y while PDSI has a value of about 0.06 DU/y (see Figure 10). Indicating a 1% - 6% increase in dryness on average across the country comparable to noted changes in Belg. The short-term dryness during Meher Season is dampened by precipitation from other seasons which factor in long-term meteorological and agricultural drought calculations. Comparison of short-term drought indicators of Meher (Figure 11) against those during Bega (Figure 3) appears to indicate that some areas that exhibit declining trends

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

during Meher exhibit increased SPI-2 during Bega, likely pointing towards shifts in late-season precipitation of Meher into Bega. While the noted drying trends during Meher are not as strong as those during other seasons, they are nonetheless significant as Meher is the major rainy season which accounts for more than 50% of the annual rainfall of the country. Therefore, even small changes in trend can imply significant changes in terms of precipitation declines. Funk et al. [20] report 50 mm – 150 mm declines in Kremit (Meher) rainfall over the last 50 year period which represents a significant proportion of water needs for many crops that are grown during the Meher season.

 doi:10.20944/preprints201908.0054.v1

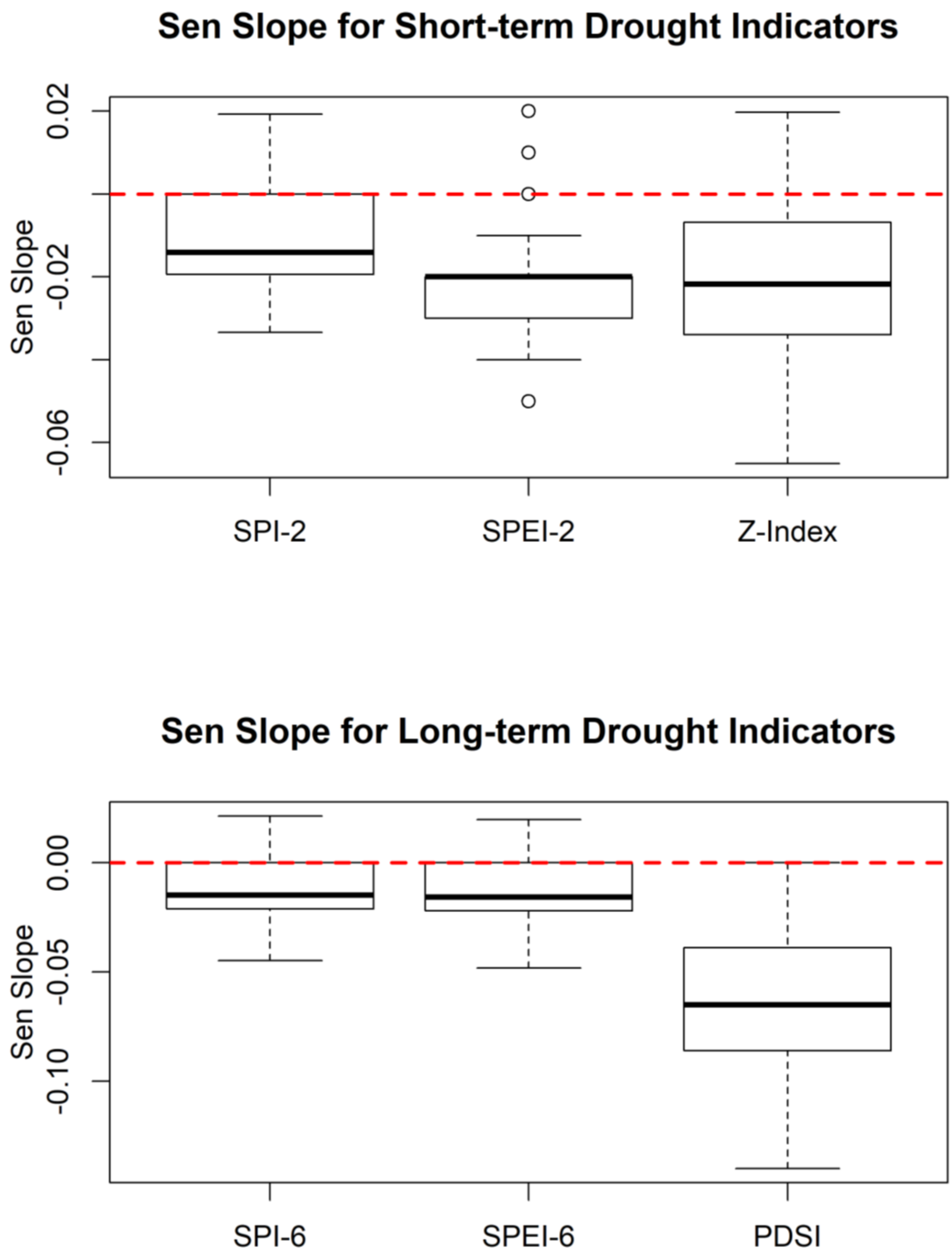

Figure 10: Variability of Sen's Slope Across Short-term and Long-term Drought Indicators

 doi:10.20944/preprints201908.0054.v1

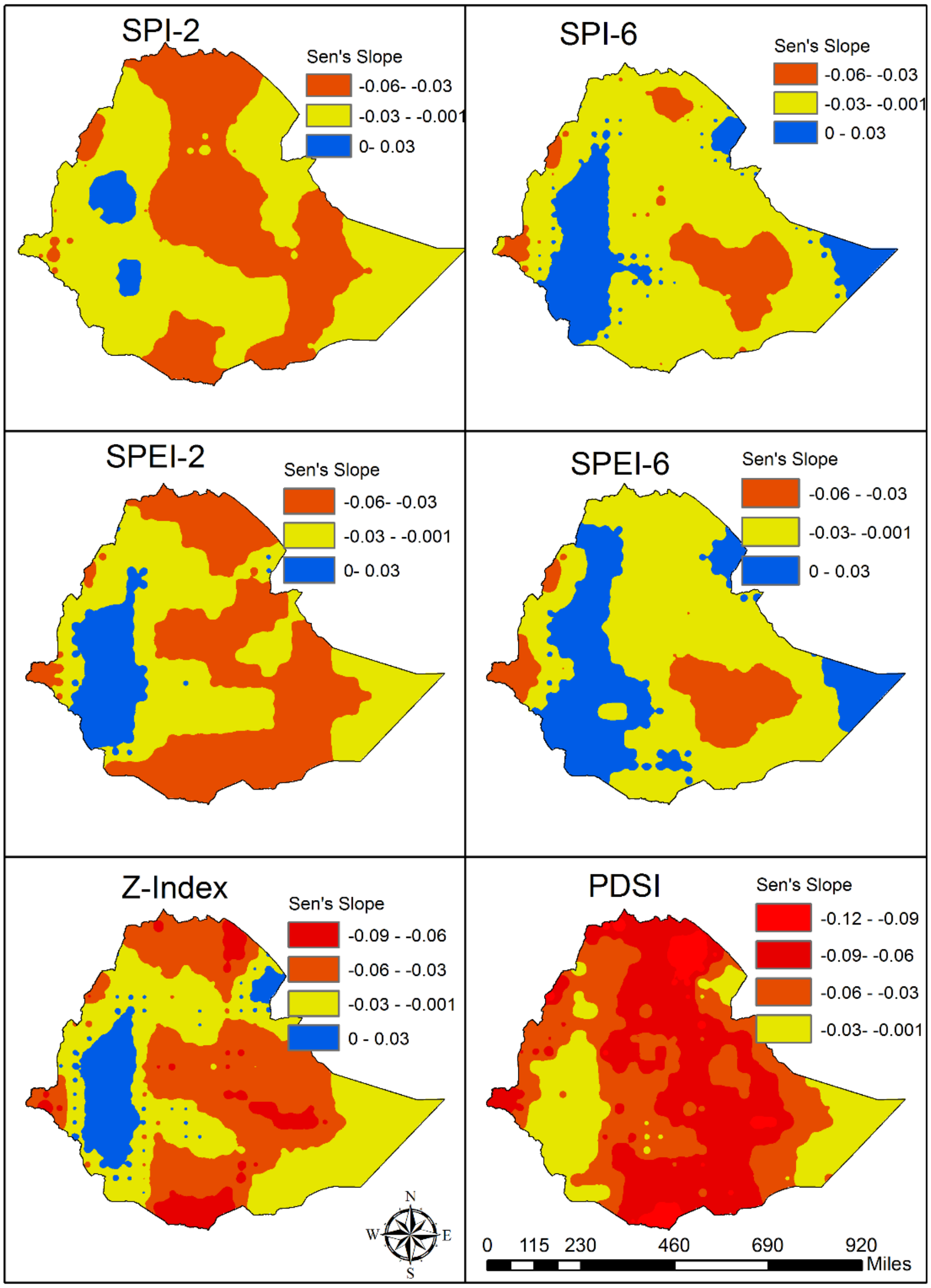

Figure 11: Variability of Sen's Slope Across Ethiopia for Various Drought Indicators

The spatial variability in drought indicators for Meher season (mapped in Figure 11) again points to the east-central band that runs across the nation. Changes in drought indicators are prominent along the Ethiopia-Eretria border but relatively subdued along the eastern borders with Sudan

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

and South Sudan. Nonetheless, the contributions of Blue Nile to overall flow of Nile is over 80% during the Meher season and even small declines in precipitation trends in the catchment area can have profound implications on these streamflows.

The drying trends noted due to precipitation declines and temperature increases in the central parts of the country (37.5° E – 42.5° E) places greater risk on agricultural production of the nation as a significant portion of agricultural lands and rangelands lie in this portion of the country (see Figure 1c). High valued crops such as corn are grown during this season and increasing drying trends in major agricultural producing regions significantly increases the risk to food and economic security of the nation.

Closing Remarks

As a rainfall dependent country, droughts can cause major economic, environmental and sociopolitical disruptions in Ethiopia. Agricultural is the primary economic driver in Ethiopia, understanding how meteorological droughts propagate through agricultural systems is of paramount importance. Given most agriculture systems are rainfed, there has been many studies that have evaluated regional trends in the Standardized Precipitation Index (SPI). However, in addition to rainfall, soil dryness caused by increased temperatures (global warming) also influences soil moisture (the master variable for defining agricultural droughts). Drought indicators that account for both precipitation and temperature effects are therefore better suited for quantifying agricultural droughts. In this study, the Standardized Precipitation Evapotranspiration Index (SPEI) and the Palmer Drought Severity Index (PDSI) and the associated Z-index are used to characterize short-term (2 month accumulation) and long-term (6 month accumulation) droughts during the three major seasons (Bega, Belg and Meher) in Ethiopia.

The results consistently indicate that SPEI-2 (two-month accumulation) was the most aggressive drought indicator for characterizing short-term droughts indicating surficial drying due to increased temperatures are important in characterizing short-term agricultural droughts. Intra-seasonal droughts over much of the country exhibited declining trends when evaluated on a century-scale (1902 – 2016). Increased winter temperatures had a major influence on Bega rainfalls. Temperature increases further exacerbated noted precipitation declines during Belg and Meher two important growing seasons in Ethiopia. In terms of rate changes, increased dryness is most pronounced during Belg (short-growing season). While the rate changes are relatively lower during Meher, the changes in the magnitude of precipitation is more as this is the major rainy season over much of Ethiopia.

Long-term (6-months) drought indicators typically had a slightly subdued response than short-term intra-season droughts but similar trends noted over the short-term also manifested in the long-term for the most part. The subdued long-term signals arise because rainfall in other seasons that get accumulated in the longer-term droughts, help buffer intra-seasonal changes. PDSI was noted to be the most assertive drought indicator for long-term droughts indicating that noted precipitation and temperature declines create a delayed but more prominent changes in hydrologic and soil moisture dynamics that other indicators (SPI and SPEI) do not capture fully in their conceptualizations.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

Increased dryness trends during Belg were noted along the eastern borders of Ethiopia with Sudan and South Sudan. These changes have the potential to increase the contentious transboundary water sharing conflicts that already exist between these nations. A band approximately between (37.5° E – 42.5° E) is a climate hot-spot where significant percent of the Ethiopia population resides and practices agricultural and pastoral activities. The increased dryness coupled with exponential population growth places an enormous stress on the agricultural systems of the country which are generally not buffered by blue water (irrigation) supplements.

The results of the study indicate that climate has changed considerably over the last century in Ethiopia which in turn has affected the drought characteristics. Agricultural systems are affected by short-term soil drying during increased temperatures. Hydrologic changes caused by precipitation declines and temperature increases act slowly but affect soil moisture availability over the growing season. Comparison of multiple drought indicators suggests that precipitation-based SPI, while useful does not provide a complete picture of long-term drought trends noted in Ethiopia. Temperature increases tend to negate precipitation increases noted in some parts of the country. Therefore, it is recommended that multiple drought indicators be used during water policy planning and management endeavors. The creation of a national-scale soil moisture sensing program (along with other factors that help conduct soil water budgets) should be a top-priority for sustaining rainfed agricultural dependent economy of Ethiopia

Acknowledgments

We thank the Ministry of Education, Government of Ethiopia and the Jimma Institute of Technology for extending their support to this research. The logistic support provided by Dr. Job Kasule is also gratefully acknowledged.

Author Contributions

Conceptualization, Venkatesh Uddameri and Elma Hernandez; Data curation, Dawd Temam and Ghazal Mohammadi; Formal analysis, Dawd Temam; Funding acquisition, Stephen Ekwaro-Osire; Investigation, Dawd Temam; Methodology, Venkatesh Uddameri; Project administration, Stephen Ekwaro-Osire; Software, Venkatesh Uddameri; Supervision, Venkatesh Uddameri; Validation, Elma Hernandez; Visualization, Dawd Temam; Writing – original draft, Venkatesh Uddameri; Writing – review & editing, Ghazal Mohammadi, Elma Hernandez and Stephen Ekwaro-Osire.

References

1. Ewonetu, G. Identifing Major Constraints of Ground Water Use for Irrigated Crop Production: Fogera Plain, North Western Ethiopia. Cornell University: 2012.

2. MoA (Ministry of Agriculture). Small-Scale Irrigation Situation Analysis and Capacity Needs Assessment; Natural Resource Management and Regulatory Department: Addis Ababa, Ethiopia: 2011.

3. McCann, J.C. A Great Agrarian Cycle? Productivity in Highland Ethiopia, 1900 to 1987. *The Journal of Interdisciplinary History* **1990**, *20*, 389-416, doi:10.2307/204084.

4. Meze-Hausken, E. Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. *Climate Research* **2004**, *27*, 19-31, doi:10.3354/cr027019.

5. Mersha, A.A.; van Laerhoven, F. The interplay between planned and autonomous adaptation in response to climate change: Insights from rural Ethiopia. *World Development* **2018**, *107*, 87-97, doi:10.1016/j.worlddev.2018.03.001.

6. Wagesho, N.; Goel, N.K.; Jain, M.K. Temporal and spatial variability of annual and seasonal rainfall over Ethiopia. *Hydrological Sciences Journal* **2013**, *58*, 354-373,

doi:10.1080/02626667.2012.754543.

7. Korecha, D.; Sorteberg, A. Validation of operational seasonal rainfall forecast in Ethiopia. *Water Resources Research* **2013**, *49*, 7681-7697, doi:10.1002/2013WR013760.

8. Dinku, T.; Connor, S.J.; Ceccato, P.; Ropelewski, C.F. Comparison of global gridded precipitation products over a mountainous region of Africa. *International Journal of Climatology* **2008**, *28*, 1627-1638, doi:10.1002/joc.1669.

9. Seleshi, Y.; Zanke, U. Recent changes in rainfall and rainy days in Ethiopia. *International Journal of Climatology* **2004**, *24*, 973-983, doi:10.1002/joc.1052.

10. Ofcansky, T.P., Laverle B.B. *Ethiopia: a country study*; Federal Research Division: Washington, D.C.:1991.

11. Verdin, J.; Funk, C.; Senay, G.; Choularton, R. Climate science and famine early warning. *Philosophical Transactions of the Royal Society B: Biological Sciences* **2005**, *360*, 2155-2168, doi:10.1098/rstb.2005.1754.

12. Mekuyie, M.; Jordaan, A.; Melka, Y. Understanding resilience of pastoralists to climate change and variability in the Southern Afar Region, Ethiopia. *Climate Risk Management* **2018**, *20*, 64-77, doi:10.1016/j.crm.2018.02.004.

13. Megersa, B.; Markemann, A.; Angassa, A.; Valle Zárate, A. The role of livestock diversification in ensuring household food security under a changing climate in Borana, Ethiopia. *Food Security* **2014**, *6*, 15-28, doi:10.1007/s12571-013-0314-4.

14. Degefu, M.A.; Bewket, W. Trends and spatial patterns of drought incidence in the omo-ghibe river basin, ethiopia. *Geografiska Annaler: Series A, Physical Geography* **2015**, *97*, 395-414, doi:10.1111/geoa.12080.

15. Edossa, D.C.; Babel, M.S.; Das Gupta, A. Drought Analysis in the Awash River Basin, Ethiopia. *Water Resources Management* **2010**, *24*, 1441-1460, doi:10.1007/s11269-009-9508-0.

16. Seleshi, Y.; Camberlin, P. Recent changes in dry spell and extreme rainfall events in Ethiopia. *Theoretical and Applied Climatology* **2006**, *83*, 181-191, doi:10.1007/s00704-005-0134-3.

17. Bewket, W.; Conway, D. A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. *International Journal of Climatology* **2007**, *27*, 1467-1477, doi:10.1002/joc.1481.

18. Cheung, W.H.; Senay, G.B.; Singh, A. Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. *International Journal of Climatology* **2008**, *28*, 1723-1734, doi:10.1002/joc.1623.

19. Rientjes, T.H.M.; Haile, A.T.; Kebede, E.; Mannaerts, C.M.M.; Habib, E.; Steenhuis, T.S. Changes in land cover, rainfall and stream flow in Upper Gilgel Abbay catchment, Blue Nile basin –

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 August 2019 doi:10.20944/preprints201908.0054.v1

Ethiopia. *Hydrology and Earth System Sciences* **2011**, *15*, 1979-1989, doi:10.5194/hess-15-1979-2011.

20. Funk, C.; Rowland, J.; Eilerts, G.; Kebebe, E.; Biru, N.; White, L.; Galu, G. A climate trend analysis of Ethiopia. *US Geological Survey, Fact Sheet* **2012**, *3053*.

21. Viste, E.; Korecha, D.; Sorteberg, A. Recent drought and precipitation tendencies in Ethiopia. *Theoretical and Applied Climatology* **2013**, *112*, 535-551, doi:10.1007/s00704-012-0746-3.
22. Wondie, M.; Terefe, T. Assessment of drought in Ethiopia by using self-calibrated Palmer Drought Severity Index. *International Journal of Engineering, Management and Sciences* **2016**, *7*, 108-117.

23. Bekele, D.; Alamirew, T.; Kebede, A.; Zeleke, G.; Melese, A.M. Analysis of rainfall trend and variability for agricultural water management in Awash River Basin, Ethiopia. *Journal of Water and Climate Change* **2016**, *8*, 127-141, doi:10.2166/wcc.2016.044.

24. Abebe, G. Long-term climate data description in Ethiopia. *Data in brief* **2017**, *14*, 371-392, doi:10.1016/j.dib.2017.07.052.

25. Suryabhagavan, K.V. GIS-based climate variability and drought characterization in Ethiopia over three decades. *Weather and Climate Extremes* **2017**, *15*, 11-23, doi:10.1016/j.wace.2016.11.005.

26. Asfaw, A.; Simane, B.; Hassen, A.; Bantider, A. Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. *Weather and Climate Extremes* **2018**, *19*, 29-41, doi:10.1016/j.wace.2017.12.002.

27. Easterling, D.R.; Evans, J.L.; Groisman, P.Y.; Karl, T.R.; Kunkel, K.E.; Ambenje, P. Observed Variability and Trends in Extreme Climate Events: A Brief Review. *Bulletin of the American Meteorological Society* **2000**, *81*, 417-426, doi:10.1175/1520-0477(2000)081<0417:OVATIE>2.3.CO;2.

28. Keyantash, J.; Dracup, J.A. The Quantification of Drought: An Evaluation of Drought Indices. *Bulletin of the American Meteorological Society* **2002**, *83*, 1167-1180, doi:10.1175/1520-0477-83.8.1167.

29. Mishra, A.K.; Singh, V.P. A review of drought concepts. *Journal of Hydrology* **2010**, *391*, 202-216, doi:10.1016/j.jhydrol.2010.07.012.

30. Wells, N.; Goddard, S.; Hayes, M.J. A Self-Calibrating Palmer Drought Severity Index. *Journal of Climate* **2004**, *17*, 2335-2351, doi:10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2.

31. Karl, T.R. The Sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their Calibration Coefficients Including Potential Evapotranspiration. *Journal of Climate and Applied Meteorology* **1986**, *25*, 77-86, doi:10.1175/1520-0450(1986)025<0077:TSOTPD>2.0.CO;2.

32. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*

2009, *23*, 1696-1718, doi:10.1175/2009JCLI2909.1.

33. Potop, V. Evolution of drought severity and its impact on corn in the Republic of Moldova. *Theoretical and Applied Climatology* **2011**, *105*, 469-483, doi:10.1007/s00704-011-0403-2.

34. Wang, D.; Hejazi, M.; Cai, X.; Valocchi, A.J. Climate change impact on meteorological, agricultural, and hydrological drought in central Illinois. *Water Resources Research* **2011**, *47*, doi:10.1029/2010WR009845.

35. Zambreski, Z.T.; Lin, X.; Aiken, R.M.; Kluitenberg, G.J.; Pielke Sr, R.A. Identification of hydroclimate subregions for seasonal drought monitoring in the U.S. Great Plains. *Journal of Hydrology* **2018**, *567*, 370-381, doi:10.1016/j.jhydrol.2018.10.013.

36. Karamouz, M.; Rasouli, K.; Nazif, S. Development of a Hybrid Index for Drought Prediction: Case Study. *Journal of Hydrologic Engineering* **2009**, *14*, 617-627, doi:10.1061/(ASCE)HE.1943-5584.0000022.

37. Sepulcre-Canto, G.; Horion, S.; Singleton, A.; Carrao, H.; Vogt, J. Development of a Combined Drought Indicator to detect agricultural drought in Europe. *Natural Hazards and Earth System Sciences* **2012**, *12*, 3519-3531, doi:10.5194/nhess-12-3519-2012.

38. Ziese, M.; Schneider, U.; Meyer-Christoffer, A.; Schamm, K.; Vido, J.; Finger, P.; Bissolli, P.; Pietzsch, S.; Becker, A. The GPCC Drought Index – a new, combined and gridded global drought index. *Earth System Science Data* **2014**, *6*, 285-295, doi:10.5194/essd-6-285-2014.

39. Uddameri, V.; Singaraju, S.; Hernandez, E.A. Is Standardized Precipitation Index (SPI) a Useful Indicator to Forecast Groundwater Droughts? — Insights from a Karst Aquifer. *JAWRA Journal of the American Water Resources Association* **2019**, *55*, 70-88, doi:10.1111/1752-1688.12698.

40. Hernandez, E.A.; Uddameri, V. Standardized precipitation evaporation index (SPEI)-based drought assessment in semi-arid south Texas. *Environmental Earth Sciences* **2014**, *71*, 2491-2501, doi:10.1007/s12665-013-2897-7.

41. Schneider, U.; Finger, P.; Meyer-Christoffer, A.; Rustemeier, E.; Ziese, M.; Becker, A. Evaluating the Hydrological Cycle over Land Using the Newly-Corrected Precipitation Climatology from the Global Precipitation Climatology Centre (GPCC). *Atmosphere* **2017**, *8*, doi:10.3390/atmos8030052.

42. Harris, I.; Jones, P.D.; Osborn, T.J.; Lister, D.H. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology* **2014**, *34*, 623-642, doi:10.1002/joc.3711.

43. Becker, A.; Finger, P.; Meyer-Christoffer, A.; Rudolf, B.; Schamm, K.; Schneider, U.; Ziese, M. A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. *Earth System Science Data* **2013**, *5*, 71-99, doi:10.5194/essd-5-71-2013.

44. Stagge, J.H.; Tallaksen, L.M.; Gudmundsson, L.; Van Loon, A.F.; Stahl, K. Candidate Distributions for Climatological Drought Indices (SPI and SPEI). *International Journal of Climatology* **2015**, *35*, 4027-4040, doi:10.1002/joc.4267.

45. Dai, A. Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. *Journal of Geophysical Research: Atmospheres* **2011**, *116*, doi:10.1029/2010JD015541.

46. Liu, X.; Zhu, X.; Pan, Y.; Bai, J.; Li, S. Performance of different drought indices for agriculture drought in the North China Plain. *Journal of Arid Land* **2018**, *10*, 507-516, doi:10.1007/s40333-018-0005-2.

47. Hamed, K.H.; Rao, A.R. A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology* **1998**, *204*, 182-196, doi:10.1016/S0022-1694(97)00125-X.

48. Yue, S.; Pilon, P.; Cavadias, G. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology* **2002**, *259*, 254-271, doi:10.1016/S0022-1694(01)00594-7.

49. Rao, A.R.; Hamed, K.H.; Chen, H.-L. Time domain analysis. In *Nonstationarities in Hydrologic and Environmental Time Series*, Springer: 2003; pp. 27-55.

50. Yue, S.; Wang, C. The Mann-Kendall Test Modified by Effective Sample Size to Detect Trend in Serially Correlated Hydrological Series. *Water Resources Management* **2004**, *18*, 201-218, doi:10.1023/B:WARM.0000043140.61082.60.

51. Khaliq, M.N.; Ouarda, T.B.M.J.; Gachon, P.; Sushama, L.; St-Hilaire, A. Identification of hydrological trends in the presence of serial and cross correlations: A review of selected methods and their application to annual flow regimes of Canadian rivers. *Journal of Hydrology* **2009**, *368*, 117-130, doi:10.1016/j.jhydrol.2009.01.035.

52. Önöz, B.; Bayazit, M. Block bootstrap for Mann–Kendall trend test of serially dependent data. *Hydrological Processes* **2012**, *26*, 3552-3560, doi:10.1002/hyp.8438.

53. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria: 2019.

54. Pierce, D. ncdf4: Interface to Unidata netCDF (Version 4 or Earlier) Format Data Files. 2017. pp 36. Available online: https://cran.r-project.org/web/packages/ncdf4/ncdf4.pdf

55. Gudmundsson, L.S.; Stagge, J.H. SCI: Standardized Climate Indices such as SPI, SRI or SPEIR package version 1.0. 2016. pp 12. Available online: https://cran.r-project.org/web/packages/SCI/SCI.pdf

56. Zhong, R.; Chen, X.; Wang, Z.; Lai, C. scPDSI: Calculation of the Conventional and Self-Calibrating Palmer Drought Severity Index. 2018. pp 7. Available online: https://cran.r-project.org/web/packages/scPDSI/scPDSI.pdf

57. Patakamuri, S. K.; O'Brien, N. Modified Versions of Mann Kendall and Spearman's Rho Trend Tests. 2019. pp 18. Available online: https://cran.r-project.org/web/packages/modifiedmk/modifiedmk.pdf

58. Rosell, S.; Holmer, B. RAINFALL CHANGE AND ITS IMPLICATIONS FOR BELG HARVEST IN SOUTH WOLLO, ETHIOPIA. *Geografiska Annaler: Series A, Physical Geography* **2007**, *89*, 287-299, doi:10.1111/j.1468-0459.2007.00327.x.

59. Byrne, M.P.; Pendergrass, A.G.; Rapp, A.D.; Wodzicki, K.R. Response of the Intertropical Convergence Zone to Climate Change: Location, Width, and Strength. *Current Climate Change Reports* **2018**, *4*, 355-370, doi:10.1007/s40641-018-0110-5.