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Reduced complexity model for assessing patterns of rainfall erosivity in Africa

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ABSTRACT

Multivariate geostatistical modeling can be used to generate spatial patterns of hydro-climate data over ungauged regions, but these models may be unsuitable when the hydro-climatological data available over large and remote areas are sparse and show different scales of resolution. In these cases, reduced complexity modeling can be better used in order to increase understanding of hydrological extremes at spatial scales and over time periods not covered by rainfall records. In this study we present and evaluate the African Rainfall Erosivity Subregional Empirical Downscaling (ARESED) model which has been developed based on hydro-climatological and geotopographic data from 46 stations across Africa with very varied climates and elevations. We spatially downscale the 85th percentile of monthly precipitation, based on several decades of data, from 50 km to 10 km grid squares in order to predict values of rainfall erosivity across Africa. This yields inputs comparable to values based on the standard Revised Universal Soil Loss Equation (RUSLE). The 46 African stations were chosen for model development because they are also sites for which there are RUSLE-based erosivity values. Once parameterized to capture mean rainfall erosivity over several decades, the ARESED model was run as a validation tool, comparing the output with actual erosivity data. On a continental scale and over decadal time scales, the ARESED model captures most of the important processes within the hydro-climatological system. Its reduced complexity structure also makes it suitable for application to regional management and environmental planning.

1. Introduction

Changes in precipitation under conditions of climate changes will influence land surface hydro-climatological processes and the maintenance of rain-fed agricultural systems (Williams and Kniveton, 2012). This is particularly the case over continents where powerful rainstorms of varying intensity drive land surface responses, such as soil erosion, over spatial and temporal scales that are relevant for environmental policy and planning (Wainwright and Mulligan, 2004; Volk et al., 2010). Over large spatial scales and where data are scarce, multivariate geostatistical modeling has been used to examine these hydro-climatological processes (e.g., de Wit et al., 2008). However, the robustness of these models is contingent on data availability, which may vary over different spatial and temporal scales of analysis (Diodato et al., 2010). Easily-accessible hydro-climatological models that address local-scale land management needs are an important management policy tool in data-poor areas such as much of Africa. This serves as the motivation to develop a reduced complexity model that can be applied to vulnerable African landscapes, identified by the Intergovernmental Panel on Climate Change as at risk from future climate change (Boko et al., 2007).

1.1. African climate and rainfall erosivity

The wide range of latitude, relief and ecosystems found across Africa results in diverse patterns of convective and orographic-driven precipitation. These patterns are linked to seasonal migration of the Intertropical Convergence Zone (ITCZ) over central Africa and monsoon-driven circulation over eastern Africa (Hastenrath and Lamb, 1978; Nicholson, 2000; Ruiz-Barradas et al., 2003) (Fig. 1). Within the ITCZ are intense convective storms of short duration with two wet seasons. Farther from the equator, only one rainy season is present and the climate is more monsoonal. This range of precipitation sources and their seasonal variability pose challenges for prediction of precipitation amounts and their timing (Reason et al., 2006), since climate models show that some types of atmospheric circulation systems have higher predictability than others (Matthews, 2005).

Recent studies have shown that spatial and temporal patterns of precipitation extremes across Africa have changed significantly over recent decades as a result of a combination of natural and anthropogenic climate changes (Sveinsson et al., 2003; Seidel et al., 2008), hydro-climatological feedbacks through variations in land use and ecosystems, and inappropriate water resource management practices (Grimm et al., 2008). Furthermore, systematic changes in the position and rainfall properties of the ITCZ and east African monsoon are also

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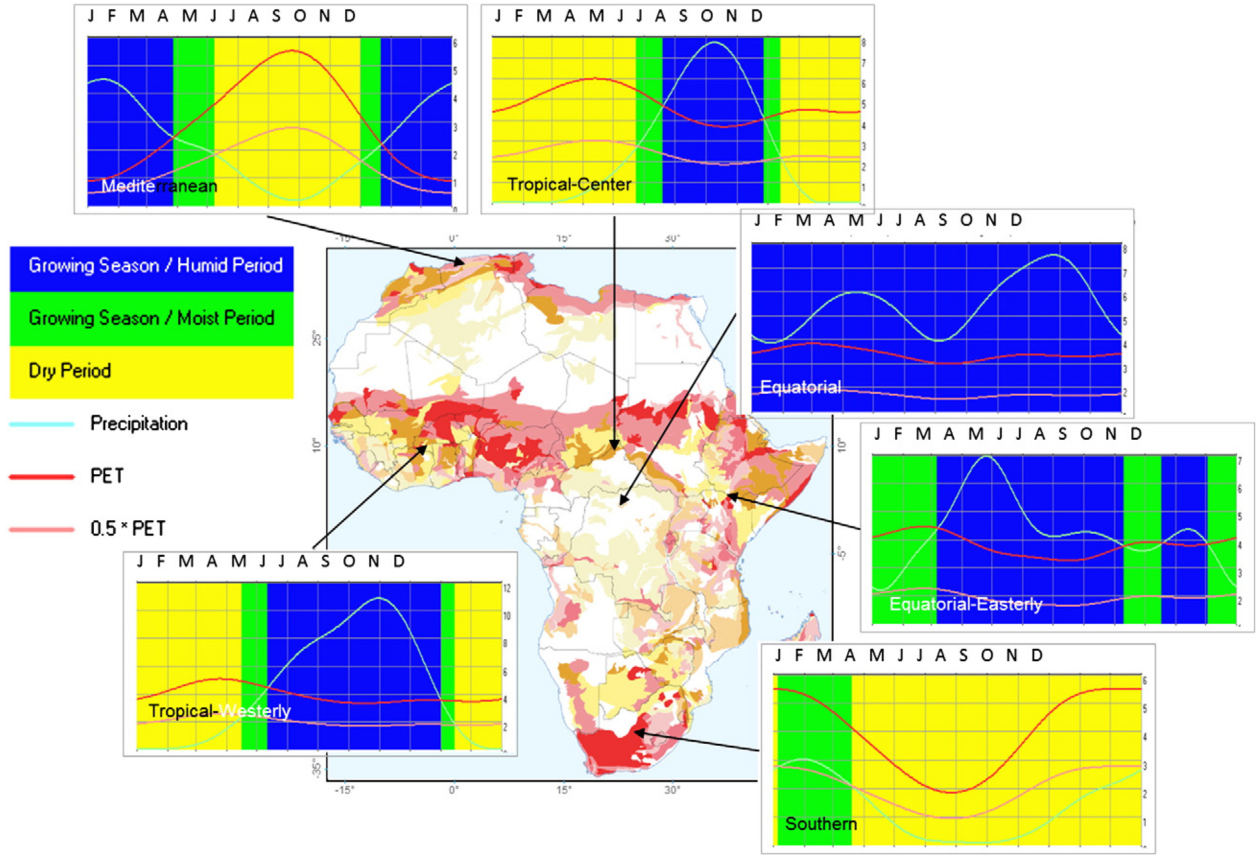

Fig 1. Map of land degradation and susceptibility across Africa, with increasing of sensitivity from yellow to red on the central map (from http://na.unep.net/atlas/africaWater/downloads/Africa_Water_Atlas_Executive_Summary.pdf), and representations of the seasonal regime of temperature and precipitation for different African regions (arranged by New-LocClim FAO software, http://www.fao.org/sd/2002/EN1203_en.htm).

noted as global climate 'tipping points' that have potential to lead to very significant and possibly unanticipated consequences (Lenton et al., 2008).

High-magnitude rainstorm events are a significant control on rainfall erosivity (González-Hidalgo et al., 2009). Rainstorm events are explicitly considered within the (Revised) Universal Soil Loss Equation (RUSLE) family as a function of breakpoint rainfall intensity kinetic energy calculated over a 30-minute period (EI_{30}). However, field measurements of rainfall volumes and intensities are recorded (and averaged) over different time intervals (Salvador Sanchis et al., 2008; Sharma et al., 2011; Meusburger et al., 2012). This means that calculated values of EI_{30} are strongly dependent on rainfall data quality and availability, and often alternative measures of rainfall intensity are used such as the Fournier index (Munka et al., 2007; Shamshad et al., 2008). As a result, the estimation of event-scale rainfall-induced land surface runoff is the greatest limitation in the prediction of sediment yield based on the RUSLE (Kinnell, 2010; Dabney et al., 2011).

1.2. Limitations of rainfall erosivity models

Application of the RUSLE is best served where data are available of high spatial and temporal resolution that can capture individual rainstorm events, particularly those of high magnitude/short duration. Data availability is a key problem in the application of the RUSLE to many areas of Africa (Sonneveld et al., 2011). The high spatial and temporal variability of rainstorms and rainy seasons across Africa (Fig. 1) also means that averaged intensity or monthly rainfall totals, as used by the Fournier index, may be not representative of event-scale conditions (Elagib, 2011). This contrasts with the European mid-latitudes where such averaged values can be used more reliably (e.g., Angulo-Martínez and Beguería, 2009; Grauso et al., 2010). As a result, many areas of Africa experience problems in calculations of rainfall erosivity using the RUSLE, because of the low spatial and/or temporal resolution of rainfall data and natural variability in precipitation patterns.

1.3. Aims and objectives

In response to these limitations, we have developed a parsimonious climate-driven model named ARESED (African Rainfall Erosivity Subregional Empirical Downscaling), in order to investigate rainfall erosivity over the African continent that consists of several regions lacking distributed data. The model incorporates monthly precipitation percentiles and geographic data that are able to capture climatic variability and rainfall erosivity over decadal time scales and across continental to other regional spatial scales, and can be put together and applied using data that are freely available on the web. As many regions of Africa are frequently exposed to aggressively-erosive precipitation, this model can consider not only changes in climate patterns (based on monthly precipitation data) but also their practical implications for soil and water protection and environmental planning and management.

In this context, the objectives of this paper are to (1) present the formulation of the ARESED model, including the meteorological stations that are used to train and calibrate the model (given in Section 2). (2) We then test the model's performance and assumptions and compare its results against previously-published field and modeled (using RUSLE) erosivity data from specific sites across Africa (Section 3). (3) We finally highlight the application of the ARESED model for practical soil erosion management purposes across regions for which there is low spatial and/or temporal data resolution (Section 4).