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Evaluating the soil moisture retrievals for agricultural drought monitoring over Brazil

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Abstract

A model for monitoring agricultural drought (SIMAGRI) has been developed in Brazil. This model is based on gridded precipitation product, real evapotranspiration calculated from vegetation index data (as proposed by [1]), and soil water storage. The soil water storage is derived from the estimation of field capacity and wilting point using pedo-transfer functions (PTFs). The SIMAGRI model suggest that the soil moisture influence is unquestionably a quantitative indicator of drought. In addition, using this model, it is possible to monitor drought episodes in agricultural regions of Brazil, especially over the Northeast, where vulnerability to drought is the highest in the country due to the prevalence of rain fed agricultural practice and frequent droughts.

1. Introduction

Impact of droughts can be classified as direct or indirect. Examples of direct impacts include limited public water supplies, crop loss and damage to buildings due to terrain subsidence and reduced energy production. Nevertheless, because of the dependence of livelihoods and economic sectors on water, most drought impacts are indirect. These indirect effects can propagate quickly through the economic system, including trade, affecting regions far from where the drought originates. Indirect impacts may affect ecosystems and biodiversity, human health, commercial shipping and forestry. In extreme cases, drought may result in temporary or permanent unemployment or even business interruption, and may lead to malnutrition and disease in more vulnerable countries [2].

In the last decade, drought episodes have had a strong impact on agricultural and livestock production in Brazil. For example, the 2012/2013 drought over the Brazilian Northeast resulted in economic losses of US$1.6 billion for the 10 most important crops (beans, rice, corn, cotton, bananas, sugarcane, cassava, soybeans and coffee), US$1.5 billion due to livestock mortality and more than US$1.5 billion in insurance claims, according to the Brazilian Institute of Geography and Statistics [3]. The 2012-2016 drought in Northeast and Southeast region, considered the worst drought in decades, has led to the promotion of Drought Preparedness and adaptation policies and resilience to climate change [4-6]. Considering only the 2015-2016 hydrological year, the drought affected about 12 million people, more than those living in the semiarid region. With respect to economic losses, approximately US$263 million were spent on the Crop Guarantee Insurance [7].

Therefore, considering the relevance of soil moisture in agriculture, this study aim at evaluating the soil moisture derived from the system of monitoring and alert of agricultural drought (SIstema de Monitoramento e Alerta para aGRIculture, SIMAGRI) in Brazil. The methodology integrates a new rainfall product inferred from on-ground radar, meteorological stations and satellite data measurements, and the Enhanced Vegetation Index (EVI) [6]. Daily precipitation data were used, considering both information provided by weather stations and satellite products. In order to assess the soil moisture estimation with SIMAGRI model, a study over Brazil from October to December 2020 was carried out.

2. Data

For this study, the following data were used: precipitation product, real evapotranspiration calculated from vegetation index data and soil properties physics.

A consistent rainfall database is critical for numerous applications. SIMAGRI model uses rainfall information for deriving soil moisture (SM) at root zone. However, to obtain results with a good spatial and temporal resolution is not enough. Consequently, techniques that combine data from satellites with data from existing stations come to meet this need. MERGE precipitation product had been selected for this study. MERGE was developed and operationally available by CPTEC/INPE (Center for Weather Forecasting and Climate Research/National Institute of Space Research - https://www.cptec.inpe.br). Detailed information about this product can be found in [8].

Other database used is the Enhanced Vegetation Index (EVI) product, which was used for estimation of the evapotranspiration. This product is a combination of the reflectance (ρ) in red, blue and near-infrared (NIR) bands derived from Moderate Resolution Imaging Spectroradiometer (MODIS) products. EVI takes into account red and infrared like Normalized Difference Vegetation Index (NDVI), and it is also uses the blue band to discount atmospheric influences in the index. This index was obtained on 16-day intervals and at 1 km spatial resolution and it is distributed at https://modis.gsfc.nasa.gov/data/dataprod/mod13.php.

Finally, soil properties physics were used from calculated the initial soil water storage (amount of water that can be stored in a soil profile and be available for growing crops). It was obtained from the estimation of field capacity and wilting point using pedo-transfer functions (PTFs) [9].

3. SIMAGRI model

The SIMAGRI model is a system of monitoring and alert of anomaly for agriculture in Brazil developed at National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN) and described in [10].

Mathematically, the SIMAGRI model is based on the following relation:

$$A_{(t+1)} = A_{(t)} + PRE_{(t)} - ETR_{(t)} \qquad (1).$$

where A is the available water capacity for plants (mm), PRE is precipitation (mm), t time, and ETR is the real vegetation evapotranspiration (mm).

The soil water storage available to plants is obtained from field capacity and wilting point using pedo-transfer functions (PTFs). These functions allow the estimation of hydraulic properties from basic soil properties, such as texture, carbon content and global density [9]. Pedo-transfer function (FPT) will be based on the van Genuchten retention equation, given by:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + \left|\alpha \psi_m\right|^n\right)^m} \qquad (2).$$

where θr and θs are the contents of residual water and saturation (m3 m-3), respectively; ψm the matric potential of the soil water (kPa); α (scaler for ψ_m), n and m are the empirical parameters of the van Genuchten equation assumed that m = 1 - 1/n. To relate each parameter of Equation 2 with pedological data (such as texture, organic carbon content, equivalent moisture and global density) linear regression techniques were used multiple, using a second-order polynomial with linear coefficients.

The actual evapotranspiration is estimated using the method proposed by FAO-56,

$$ET = (Kcb + Ke) * ETo \qquad (3).$$

Kcb is the crop coefficient, Ke is the evaporation coefficient of the soil, calculated according to the methodology proposed by FAO-56 and ETo is the reference evapotranspiration, which was calculated using the methodology of [1].

The Kcb is obtained from the linear relationship between NDVI and Kcb according to the relation applied by [11]:

$$Kcb = 1.64 * (NDVI - NDVI\ min) \qquad (4).$$

Where, NDVI is the vegetation index of the crop of the day studied and NDVImin is the NDVI value for exposed soil, and the value of 0.15 was adopted, Ke is the soil evaporation coefficient, calculated according to the proposed methodology by FAO-56 and ETo is the reference evapotranspiration, which was calculated using the equation:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (5).$$

where Rn is the net radiation, G is the soil heat flux, (e_s - e_a) represents the vapour pressure deficit of the air, r a is the mean air density at constant pressure, cp is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances.

Most of the effects of the various weather conditions are incorporated into the ETo estimate. Therefore, as ETo represents an index of climatic demand, Kc varies predominately with the specific crop characteristics and only to a limited extent with climate. This enables the transfer of standard values for Kc between locations and between climates. This has been a primary reason for the global acceptance and usefulness of the crop coefficient approach and the Kc factors developed in past studies. Thus, ET is obtained from different crop.

The Penman-Monteith approach as formulated above includes all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation. Most of the parameters are measured or can be readily calculated from weather data. The equation can be utilized for the direct calculation of any crop evapotranspiration as the surface and aerodynamic resistances are crop specific.

In this study, to calculate the water balance is considered that the amount of water transpired by plants depends on the soil water storage, as shown in Figure 1.

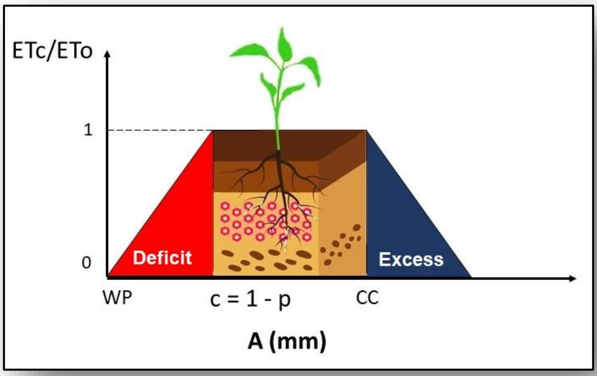

Figure 1: Ratio between actual and potential evapotranspiration as a function of soil water storage, with WP being the wilting point, CC the field capacity and p the available water fraction.

FAO suggests a simple function that considers this effect, by defining the fraction of readily available water, p, based on solutions such as those proposed by [12]. In this concept, it is assumed that this fraction p of the available water capacity (AWC) is used, there is no significant reduction in crop productivity. Therefore, water deficit is defined when storage is below the available water. However, as the objective is to prevent plants from suffering damage from water deficit, the limiting condition for this not to happen is to consider the storage of water in the soil up to (1-p) AWC, assuming that the coefficient (1-p) corresponds to a potential of -60 kPa [10].

Analyzing Figure 1, it can be seen that as the soil moisture decreases, there will be a point at which the crop evapotranspiration (ETc) becomes smaller than the reference evapotranspiration (ETo), which establishes a linear relationship between the decrease in soil moisture and the decrease in ETc/Eto.

The coefficient p indicates the proportion of the total available water that can be transpired at a potential rate (ETR=ETP). Below this storage, the ETR is proportional to the remaining storage in the profile, that is:

$$\begin{aligned} ETc &= ETo & A &> AWC\,(1-p) \\ ETc &= ETo*(A/[AWC(1-p)]) & A &\leq AWC\,(1-p) \end{aligned} \quad (5).$$

The p fraction depends on the type of soil, the sensitivity of the crop to water stress and the value of ETo.

For ten day and monthly periods, it is necessary to estimate the average real evapotranspiration taking into account the number of days where ETP = ETR. Thus, the crop evapotranspiration equations were integrated in both cases.

The balance equation solutions for each case are presented below:

a) Para $A > AWC\,(1 - p) \Rightarrow ETR = ETP$

In this case, the water balance equation is given by:

$$\frac{dA}{dt} = PRE - ETc \quad (6).$$

With dA varying between A_t and A_{t+1} and dt between t and $t + \Delta t$, we have that:

$$\int_{At}^{At+1} dA = \int_{t}^{t+\Delta t} (PRE - ET)dt$$

The solution of the differential equation above is given by:

$$A_{t+1} = A_t + (PRE - ET)\Delta_t \quad (7).$$

b) For $A \leq AWC\,(1 - p) \Rightarrow ETc = ETo\,\frac{A}{AWC(1-p)}$:

Thus, the water balance equation is solved as follows:

$$\int_{At}^{At+1} \frac{dA}{PRE - ETo\frac{A}{(1-p)AWC}} = \int_{t}^{t+\Delta t} \quad (8).$$

Solving Equation 8, the following solution is found:

$$A_{t+1} = PRE.COEF - [PRE.COEF - A_t].e^{-\Delta t/COEF} \quad (9).$$

where

$$COEF = \frac{(1-p)AWC}{ETc} \quad (10).$$

Therefore, the solution of the water balance results from the solutions of the accumulated evapotranspiration equation in the period, presented in both cases, considering Δt = 1 day in the present study.

Finally, daily soil moisture data can be calculated for different territory, considering 1m of depth and 1 km spatial resolution.

4. Results

SIMAGRI model was applied for Brazil, during the period from October to December 2020. This period was considered because it represents the beginning of the rainy season in a large part of the Brazil. Figure 2 shows SM derived by SIMAGRI. It can be is observed that the amount of water in the soil is the lowest (< 40 mm) in the Northeast region and the greatest in the North and South regions of the country, with values above 200 mm. In almost all the North region, there is a very low value of SM in October.

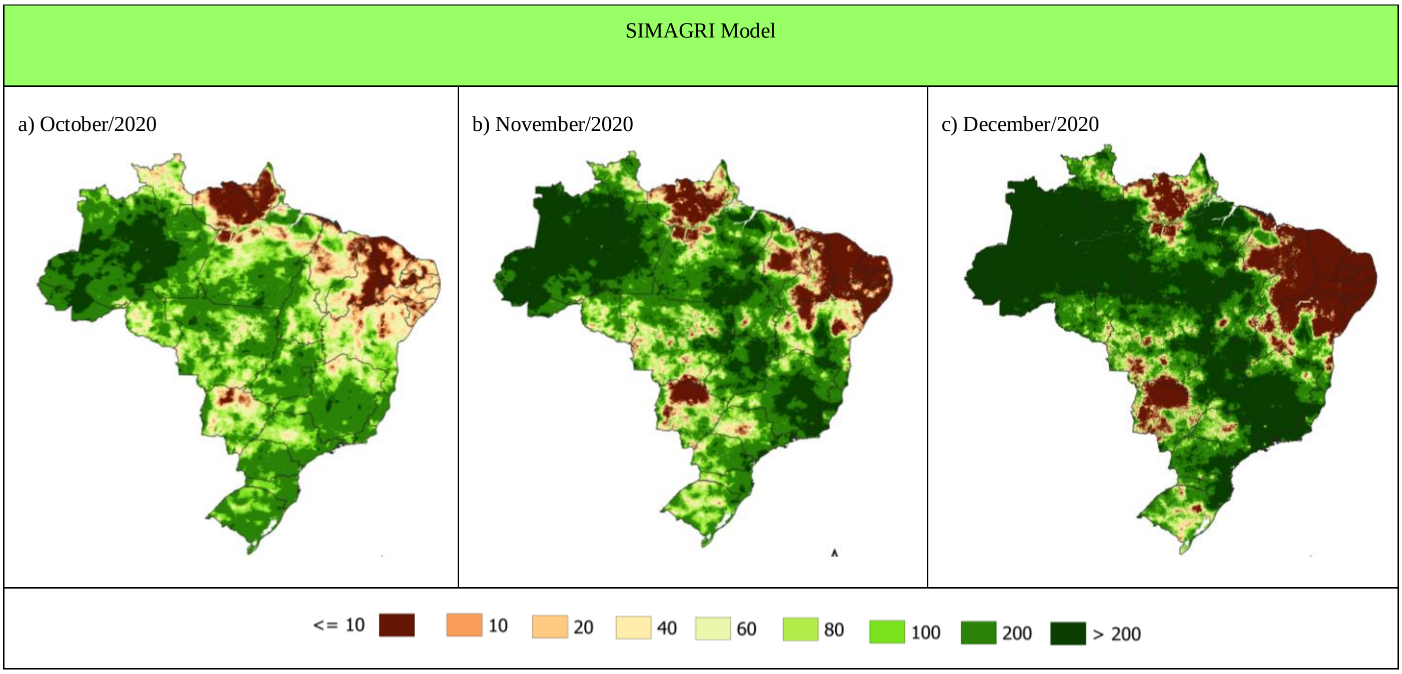

Figure 1: Spatial-temporal distribution of soil moisture (mm) derived from SIMAGRI model in Brazil, during the period from October to December/2020 (a-c) 2020, SM at 1 m depth.

In addition, it is observed that in November, SM decreases in most areas, with water deficit and expansion of water surplus areas. This tendency is even more evident in December in the central and western part of the region. The results obtained by the SIMAGRI model also show a water deficit, mainly for the months of November and December in a large part Maranhão, Piauí, Ceará and West of Rio Grande do Norte and Paraíba. Favorable conditions for the occurrence of water surpluses were observed only for the West and South of Bahia. Low water surplus values were observed in November and December in the State of Mato Grosso do Sul. This drought was caused by a meteorological blockage, characterized by the appearance of a high-pressure area that prevented the formation of rain. The combination of lack of rain with high temperatures and very low relative humidity led to an increased risk of fire, which extended not only to agricultural areas but also to natural areas of the biome. The fires in the Pantanal in 2020 were truly unprecedented. As of December 31th 2020, 22,116 fires were recorded in the biome, according to data from INPE [6]. In the Southeast region, the soil water condition indicated a predominance of deficiency over the northwest of São Paulo in the evaluated months. However, in November and December, excess water is found in several locations in the Southeast, mainly on the eastern part. In December, the situation of excess water occurred in a large part of the region. Thus, different studies demonstrated high drought induced production losses, mainly maize and beans in Northeast, and soybean and wheat in the South-eastern and Southern regions of the country [13-18].

5. Conclusions

From the results obtained with SIMAGRI model, it can be concluded that the soil moisture estimated from a monitoring and alert model of soil moisture anomalies (such as the SIMAGRI model) helps in the identification of soil water supply and demand, with more detailed information in different regions. In addition, SIMAGRI model detects the regions most impacted by droughts, affecting mainly agriculture of subsistence. Brazilian agricultural production stands out in world food security, accounting for a large part of the food produced worldwide.

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