Monitoring drought in Ghana using TAMSAT-ALERT: a new decision support system

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Introduction

Many African people are reliant on agriculture as a means of survival and are particularly sensitive to variations in rainfall. There is therefore a clear need for usable risk assessment and decision support tools for the management of agricultural drought (soil moisture deficit). This article describes an application of TAMSAT-ALERT (Tropical Applications of Meteorology using SATellite data and ground-based observations AgriculturaL EaRly warning sysTem), a decision support tool which exploits the expected persistence of root zone soil moisture anomalies to provide early warnings of agricultural drought.

The persistence of soil moisture anomalies in the deeper layers of the soil for weeks or months may be expected to lead to a degree of predictability of soil moisture deficit – even in the absence of skilful prediction of precipitation. At a given time, the probability of soil moisture deficit at some point in the future is related to the current soil moisture and the likelihood of insufficient rain in the ensuing period. Current soil moisture depends on the land surface properties (vegetation and soil texture) and the meteorological conditions over the previous days or months. The likelihood of sufficient rainfall within a particular time frame depends on the climatology, both of rainfall and of other meteorological variables that influence the water balance. The premise of this application of TAMSAT-ALERT is that after a certain date we can be confident of an ensuing drought because, even if it rains as much as it ever has before, the soil moisture will not recover to normal levels.

In essence, the system addresses the question:

> *Given the current state of the land surface and the historical climatology, what is the likelihood of agricultural drought?*

Models and data

The model used by the system is JULES (the Joint UK Land Environment Simulator), a process-based land surface model that is the land surface component of the Unified Model (UM). A land surface model translates meteorological driving data, such as rainfall, temperature and wind speed, into soil moisture and other land surface variables by solving the physical equations that govern the various land surface processes. An illustration of the main processes modelled by JULES is shown in Figure 1. The surface can be one of nine possible types: deciduous or evergreen forest, two grass types, shrubs, urban, open water, permanent land ice and bare soil. Heat and water are exchanged from the atmosphere, through any vegetation, to the surface and underlying soil. The rate of exchange of heat between the atmosphere, surface and soil is determined by energy balance equations – the energy absorbed from the sun ('radiation' in Figure 1) must ultimately balance the energy emitted through evaporation, conduction and radiation from the soil surface and/or vegetation, in addition to the transfer of heat from the surface to the underlying soil. For the purposes of this article, however, it is the hydrological aspect of the model that is of particular interest.

Soil moisture is calculated for each user-specified layer, with a default of four layers of thicknesses 0.1, 0.25, 0.65 and 2m. The moisture content of each layer is calculated from the difference between the moisture extracted by vegetation and the fluxes in and out of the layer from diffusion according to Darcy's law. Darcy's law relates the flux of water to the water pressure and porosity of the soil. The moisture extracted by vegetation is dependent on the air temperature, moisture availability and the root concentration, which decreases exponentially with depth. For the top soil layer, any inward flux at the surface is the infiltration, determined from the throughfall (rainfall that is not captured by vegetation), with a maximum infiltration rate set by the soil properties. The soil properties are controlled

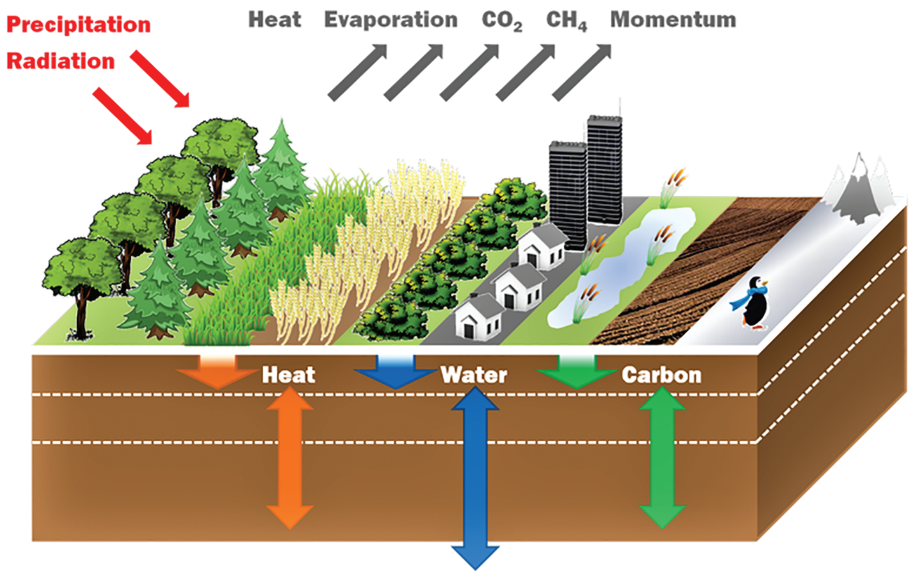

Figure 1. Illustration of the processes represented in a land surface model such as JULES. (Contains public sector information licensed under the Open Government Licence v.1.0.)

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by the sand, silt and clay soil fractions. The difference between the throughfall and the infiltration becomes the surface runoff. In the case of saturation of a soil layer, infiltration into the layer from above is prevented, and the excess moisture is stored in the layer above. If the top level becomes saturated, which may occur from excessive rainfall, the excess moisture is added to the surface runoff. The diffusive flux out of the base of the soil column is the sub-surface runoff. Photosynthesis and respiration of vegetation affect the water and heat budgets of the surface via evaporation. For full model documentation see Best *et al.* (2011) and Clark *et al.* (2011). For the applications presented in this article, JULES version 4.1 was used with the default four soil layers.

In this article, the TAMSAT-ALERT methodology is illustrated for Tamale, a locality in northern Ghana shown in Figure 2. Tamale is located at a latitude of 9°N and as such has a tropical climate, with seasons characterised by changes in rainfall instead of temperature. On average, the rainy season runs from April to October, peaking in September, and is a result of the migration of the Inter-Tropical Convergence Zone (ITCZ) during northern hemisphere summer. The growing season is strongly tied to the seasonal rains, and it is variation in the amount and timing of these rains that can cause agricultural droughts.

Daily meteorological driving data for an observing station at Tamale for 1960–present day were provided by the Ghana Meteorological Agency. The data were disaggregated to the model timesteps within the JULES system. The disaggregation imposes a diurnal cycle on the daily temperature values and partitions the daily rainfall into convective and large-scale rain events, the start time of which is randomly determined for each day but is concentrated in the early afternoon for the results shown here. The duration of such events is fixed throughout the model run at 6h. Incoming solar (shortwave) and terrestrial (longwave) radiation were not measured at this station. The incoming shortwave radiation is, therefore, derived from the location and time of day, and the longwave from the diurnalised temperature.

The hydrological and thermal soil parameters for Tamale were based on the sand, silt and clay fractions for northern Ghana given in the International Satellite Land Surface Climatology Project, Initiative II (ISLSCP II) soil texture map (Scholes and Brown de Colstoun, 2011). The resolution of this dataset is limited at 1° × 1° and as such only represents an estimate of the average soil properties over the region. The land surface types for the regions studied were obtained from the Global Land Cover Characterisation database (from the United States Geological Survey Long Term Archive, 2017) and are a combination of broadleaf vegetation, needleleaf vegetation and grass.

Method

The application of TAMSAT-ALERT, described in this article, considers the severity of agricultural drought as the mean soil moisture deficit over a user-defined period. The historical soil moisture is calculated by using historical observations to drive JULES. The historical soil moisture is the blue line in Figure 3. Multiple ensemble members are initiated from the estimate of the current state of the land surface and each is driven with an individual year's data from the climatological record. The ensemble members are the red lines in Figure 3. For each of these projections the time-mean is calculated for the whole growing season (including both the historical model run up to the present day and the projection into the future), generating a distribution of growing season-mean soil moisture values.

This distribution can provide information on the likelihood of an agricultural drought. The distribution is fitted to an empirical cumulative distribution function in order to determine the probability of the mean soil moisture falling below a user-defined threshold for 'drought'. This is based on the soil moisture climatology, which can be obtained by running JULES for the entire length of the climatological data record. The length of the climatology used ultimately depends on the data available; however, this method does require a long climatology. A length of 20–30 years ensures an adequate sample of the local climate whilst accounting for the decadal variability of African rainfall.

Summary of the method

The main elements of the method are as follows:

1. The historical soil moisture is calculated up to the present time using a land surface model.
2. From this model state the model is run forward with climatological data, with one projection for each year in the climatological record.
3. Next, the mean soil moisture is calculated for the *entire* growing season, for each of the projections. The distribution of values obtained represents the range within which the *growing-season mean* soil moisture is likely to lie by the end of the season.
4. This distribution is used to determine the probability that the mean soil moisture will be below an arbitrary drought threshold.

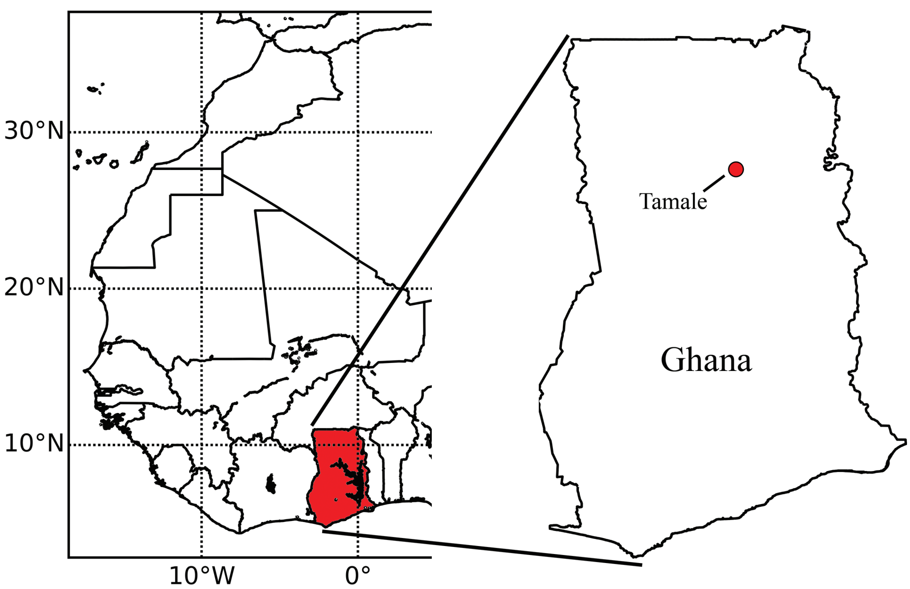

Figure 2. Map of northwest Africa showing the location of Tamale within Ghana.

Implementation of TAMSAT-ALERT for soil moisture

Figure 4 shows a series of plots for Tamale at different stages throughout the season, with the blue line showing the historical soil moisture and the red lines the climatological projections. The data for 2011, which was a dry year, with 825mm of rain, are shown in the top row, while those for 2003, which was a wet year, with 1373mm of rain, are shown in the bottom row. The climatological data used for this example are from the local meteorological station and run from 1984 to 2011.

At the start of the year the soil moisture differs by about 50kgm^{-2} between 2003 and 2011 (Figure 4). The probability that the mean soil will be in the lowest quartile of soil moisture climatology (an arbitrary drought threshold) by the end of the season is shown

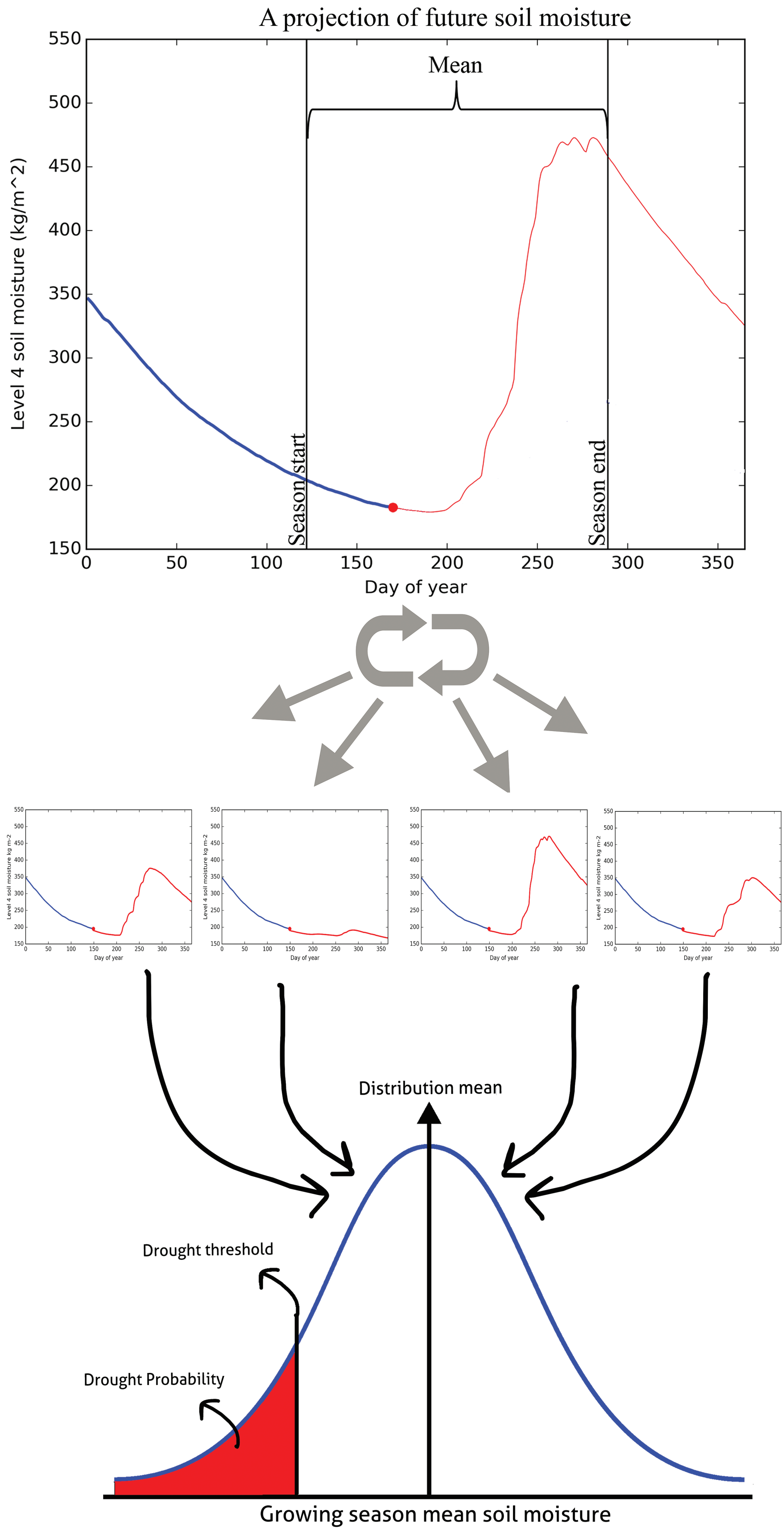

Figure 3. Diagram showing how the drought prediction tool works. Moving from top to bottom: project the current soil moisture into the future using one of the climatological years and calculate the mean over the whole growing season (between the vertical black lines); repeat this process for each year in the climatological record and fit a distribution to these means; and, finally, use the drought threshold to calculate the drought probability from the distribution. See main text for full details.

in the right-hand plot of Figure 4. At this early stage the probability for both years is close to the climatological probability, reflecting the fact that, for this region, soil moisture anomalies in the root zone do not persist from one growing season to another.

Moving forward to around the start of the growing season (day 152, Figure 4 – far left) there is still little difference in the projections for the two years because the early season rainfall, and hence the soil moisture values for both years, are similar. This is reflected in the drought probabilities, which remain close to the climatology. As the season progresses, the probability of drought diverges from the climatological probability, as the inclusion of historical information constrains the drought risk assessment. Furthermore, in 2011 by day 250 (approximately a month before the end of the rainy season), the soil in the root zone is so dry that a drought would still be expected even if the rainfall in the month before the end of the season equals the maximum for that period in the 30-year climatology. The converse is true for 2003 – once the soil is wet and the season is well advanced, even a very dry end to the season will not result in agricultural drought. Thus, it is apparent that on day 250 in 2011 drought is likely, while in 2003 it is unlikely. This illustrates the predictability ensuing from the soil moisture memory of the land surface.

The discussion so far has focused on soil moisture; however, it is possible to apply this method to other land surface and meteorological variables. For example, JULES calculates the soil moisture in user-configurable layers, which could be used as well as the total column soil moisture. JULES also calculates a *plant soil moisture availability factor*, beta, which is a function of the soil moisture and soil type (Best *et al.*, 2011). Additionally, this method can be applied to precipitation, where the total precipitation over the growing season is used instead of the mean soil moisture. This results in a prediction of meteorological drought as opposed to agricultural drought. Other metrics are currently being investigated by TAMSAT as part of ongoing trials at multiple locations in Africa.

Figure 5 shows predictions made in the middle of the season (1 July) for cumulative precipitation and mean total soil moisture over the May–October period. The year illustrated in Figure 5 is 1985 – a season with average precipitation but low soil moisture and lower than average crop yields (Food and Agriculture Organization of the United Nations, 2017). The plots in Figure 5(a) and (d) are similar to Figure 4, with the climatological range illustrated by the grey shaded area, whilst the probability density plots in Figure 5(b) and (e) show both the climatological distribution and the projected probability distribution. Figure 5(b) indicates that at this stage in the season, the cumulative precipitation for the May–October period is highly uncertain as the projected probability distribution (green line) is broad, meaning that there is an equal probability of a wide-range of precipitation totals occurring. In contrast, Figure 5(e) shows that there is a high probability of lower than usual soil moisture, as the projected probability distribution is narrower with almost no probability that the values will be in the higher end of the climatological distribution. These findings are consistent with Figures 5(c) and (f), which show that the precipitation forecast (dark grey) is close to climatology (light grey), while the soil moisture is very different from the climatology and is highly likely to be average or well-below average. The time series in Figure 5(d) suggests that the projected soil moisture deficit is associated with low soil moisture at the outset of the season.

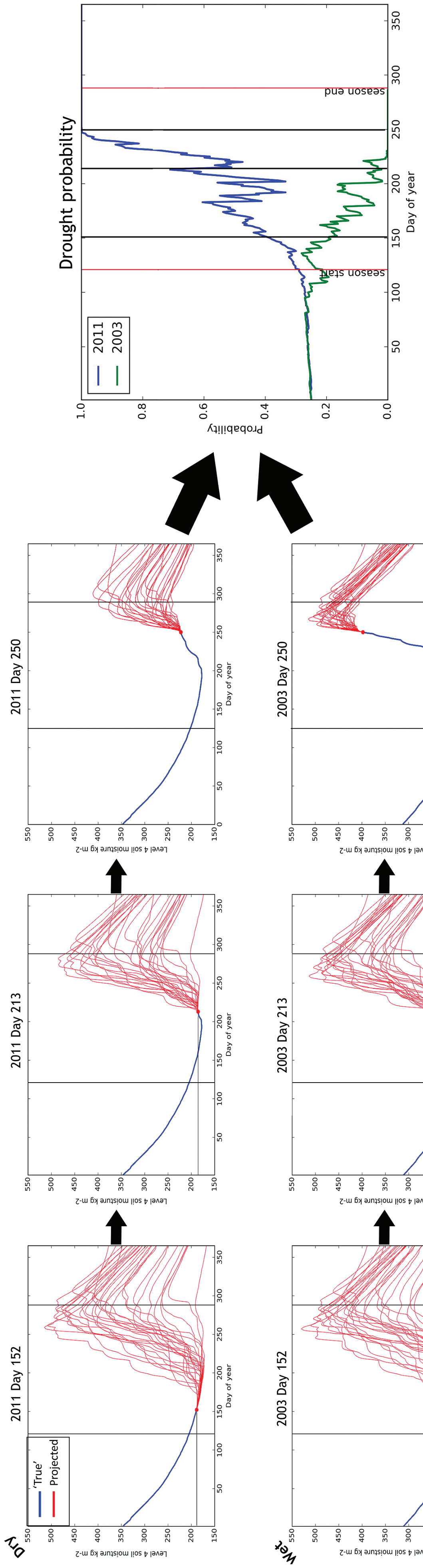

Figure 4. The 'true' historical (thick blue lines) and projected soil moisture (thin red lines), left, for 2011 (top) and 2003 (bottom) and the corresponding evolving drought probability (right), where the vertical black lines represent the location of the three left plots. The drought probability is defined here as the probability that the projected soil moisture mean for the growing season will be in the lowest quartile of climatology by the end of the season.

Discussion and conclusions

Monitoring of drought risk is of key importance for regions of Africa that depend on rainfed agriculture. In this article, we have described a methodology for deriving risk assessments for agricultural drought using a land surface model forced with a historical climatology.

For the years investigated it is clear that as the season progresses the evolving condition of the land surface is a key determinant of drought risk. In other words, if the root zone soil moisture is known, drought can be predicted with a high level of confidence several weeks before the end of the growing season – even in the absence of skilful forecasts of precipitation.

It should be noted, however, that for metrics based on the output of JULES, such as soil moisture and beta, the reliability of the forecast is affected by the ability of JULES to simulate variability in these metrics. If rainfall proxies such as TAMSAT (Maidment *et al.*, 2014; Tarnavsky *et al.*, 2014) are used in place of station data to drive the prediction model, errors in the rainfall add significant uncertainty to the soil moisture predictions (Greatrex *et al.*, 2014). In Africa, moreover, comparison of modelled soil moisture against observations is difficult, owing to the lack of reliable soil moisture observations. Current work within TAMSAT is focused on improving the root zone soil moisture estimates, including by using data assimilation techniques to incorporate remotely sensed observations of the state of the land surface into JULES.

TAMSAT-ALERT does not depend on skilful seasonal forecasts of precipitation. It is, however, possible in principle to incorporate forecast information into the drought risk assessments by weighting the climatological input into JULES. The potential additional value of seasonal forecasts of precipitation

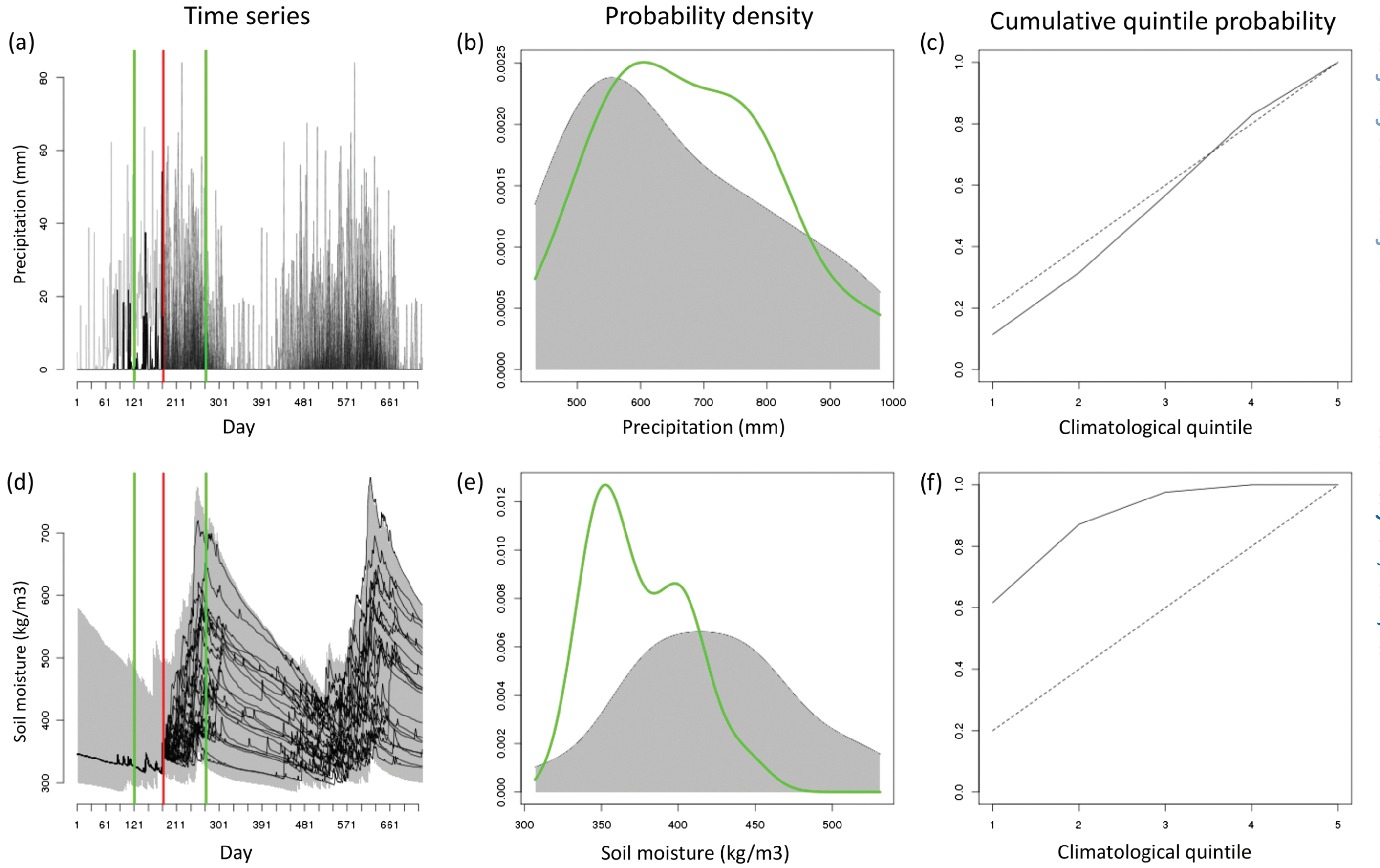

Figure 5. Left plots: Historical and projected soil moisture (black lines) and climatological range (grey shaded area) for (a) precipitation and (d) soil moisture for 1985/1986. The green vertical lines indicate the growing season and the red vertical line is the current day. Middle plots: probability density for (b) precipitation and (e) soil moisture for 1985. The grey shaded polygons are the climatology and the thick green lines are the probability density distribution for the forecast ensemble. Right plots: probability that the growing season total precipitation (c) and soil moisture mean (f) at the end of the growing season will reside in each of the 5 quintiles of the climatology (solid line) for 1985. The climatological expectation is shown as a dashed line.

for assessment of drought risk is the subject of ongoing work.

In summary, TAMSAT-ALERT is a new system for translating local climatological and meteorological monitoring data into quantitative assessments of agricultural drought as the growing season evolves. The system is currently under development, with operational pilots planned in Ghana and Kenya during the forthcoming rainy seasons.

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