Chapter 15
Application of Soil Moisture Model to Marula (*Sclerocarya birrea*): Millet (*Pennisetum glaucum*) Agroforestry System in Burkina Faso

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15.1 Introduction

15.1.1 Problem

Seasonally dry forests and savannas consisting of sparse tree canopies and dominated by open grassland make up about 16 million square kilometers of tropical land of which only 1 million worldwide remains as natural vegetation (Miles et al. 2006). The remaining seasonally dry regions are cultivated (Williams 2008). Natural vegetation is adapted to the extreme seasonality, characterized by deep taproot systems and seasonal deciduousness, whereas human propagated vegetation is not (Griffith 1961).

Watercourses and bodies in these areas are ephemeral because of the extreme seasonality of the hydroclimatic regime, which is further exacerbated by the presence of unusually high interannual rainfall variability (Murphy and Lugo 1986; Furley 2004). For example, the average total annual rainfall is 900 mm in

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Burkina Faso, but it is not unusual to have years with as little as 300 mm or as much as 1,500 mm of rain.

These regions are predicted to be sites of strong climate change (Donner and Large 2008). In Burkina Faso, precipitation isohyets have shifted to the south, reducing the average rainfall overall in the last 40 years, although some recovery has been seen in recent decades (Wittig et al. 2007). Up to 20% rainfall and 60% runoff reduction in Burkina Faso has been documented in the last decades (Mahe et al. 2005; Kallis 2008). Climate change is expected to further alter the precipitation patterns in terms of timing, even if original quantities are maintained (Hulme et al. 2000). These changes can be attributed both to regional land use, specifically vegetation change, and to global weather response to increased greenhouse gases. As a result, especially toward the middle and end of the dry season, lakes and streams become dry, while groundwater levels drop.

In a Sudanian savanna landscape, which occupies much of the country, these shifts in precipitation can be accompanied by a dramatic shift in species composition or a *sahelisation* that is irreversible due to the corresponding changes in soil physics and albedo. Zheng and Eltahir (1998) found that at a regional scale, deforestation along the coast in addition to the desert border of West Africa might be responsible for the decrease in precipitation in especially the Sahelian zone.

Resource poor farmers are among the groups most vulnerable to climate change in West Africa. Although in the Sudanian zone, less than 10% of water resources are currently exploited, these farmers have little access to the technology needed to increase access to water. Their livelihoods are almost entirely dependent on rainfed agriculture which is highly sensitive to even small fluctuations in the variability and quantity of rain. Since they are both the consumers and producers of their agricultural products, there is little external impetus for investment in climate change adaption; however, failure to adapt may result in large scale poverty, famine, migration, and possible conversion to livelihood strategies which further threaten global biodiversity and ecosystem services (Downing et al. 1997). Important adaptations include technological support to rural farmers that will allow them to predict, prepare for, and buffer the damages of climate hazards on their livelihoods.

Seasonality is the core principle of farming systems in these areas, as opposed to the temperature-driven agriculture present in temperate zones. Soils are generally fertile, and the rain is sufficient for rainfed cotton, maize, millet, and sorghum production, although the farmer must be especially attentive to anticipate and predict the rain. For example, the Yoruba know that the rain will arrive by observing changes in the leaves, the sky, and bird songs (Richards 1985). Late rainfall and poor timing of planting in relation to the rain can cause fatal problems. Although the most prosperous farmers can produce competitive crops in seasonally dry ecosystems, most farmers and their communities live in poor conditions, with food shortages, water stress, and related symptoms of poverty. Farming in valleys, floodplains, and wetlands is a tool practically unique to West Africa that is used to cope with the challenge of droughts in place of irrigation, although it can increase diversification of the generally limited crops. Paul Richards argued in 1985 that most rural farmers in West Africa (Nigeria and Sierra Leone) knew most of what agricultural science has to offer; however, they still had problems, and those were for the most part unsolved by scientific inquiry.

Two reasons explain the lack of exploitation of the water resource. The first is the difficulty for local population to manage a water resource characterized by very intense rainfalls followed by long dry seasons. During the wet season, runoff and erosion are extreme, but the recharge is limited due to actively transpiring vegetation and shallow soils. This suggests that lack of water is not necessarily the primary constraint and that even a doubling of crop yields would be hydrologically possible with relatively small manipulations of rainwater partitioning in the water balance. The second reason is the poor management of agricultural lands, grazing (Rockstrom and Falkenmark 2000), fires induced by humans (Delmas et al. 1991), and forest clearing (Fries and Heermans 1992; Savadogo et al. 2007). These activities have increased erosion, soil loss, loss of nutrients and organic matter, and altered natural stream ecology and regime. This poor management is due to the low understanding of natural phenomena, lack of management tools, and a low level of environmental education of the communities and the authorities (Wallace and Gregory 2002; Schuol et al. 2008).

15.1.2 Solution: Agroforestry

Seasonally dry ecosystems offer great possibilities for sustainable and profitable management of cultivated and natural areas (Fries and Heermans 1992). Improving rainfed agriculture by increasing the use of the portion of rainfall that infiltrates the soil and is accessible by plants to generate vapor flow in support of biomass growth (Falkenmark and Rockstrom 2006) is a commonly suggested solution.

Agroforestry, or the mixed planting of trees with crops, has long been practiced in West Africa (Neumann et al. 1998). Cannell proposed the central biophysical hypothesis of agroforestry to be that “the benefits of trees and crops only exist when trees can acquire resources of water, light, and nutrients that crops would otherwise not acquire” (Cannell et al. 1996). When they are water limiting, they increase the yield when increase the fraction of rainfall in plant growth. Improving water use efficiency by crops is an important tool to promote resilience in the face of occurring and predicted climate change (Thomas 2008). Optimizing the water use by trees benefitting from the unused crop water is an opportunity for adaption. The livelihood benefits are even more significant when one considers the added value that trees offer to agricultural land in terms of nontimber products, particularly in years of crop failure due to irregular weather patterns which are expected to become common in West Africa.

Reductions in soil moisture are one of the main reasons why farmers are resistant to adopting intensive agroforestry practices (Ong and Leaky 1999). Agroforestry solutions that emphasize the spatial arrangement of trees and crops accross differences in topography and soil variation may be the most beneficial to minimize root competition between crops and trees (Ong et al. 2002). Pruning or separating roots is shown as effective to separate the root space of the crops and trees as well. Some argue that agriculture must mimic a natural savanna ecosystem, where there is evidence of clear niche partitioning between the shallow water used by grasses and the deep water drawn by trees.

Shade offered by tree canopies may alter the subcanopy microclimate and thus the optimal species. Jonsson et al. (1999) found significant competition for light resources demonstrated by reduction in yields between millet crops and parkland shea nut (*Vitellaria paradoxa)* and African mustard trees (*Parkia biglobosa*). Optimizing agroforestry potential may be a matter of matching possible shade preferring crops with appropriate radiation shields offered by specific canopies rather than incorporating dominate crop into canopy space (Jonsson et al. 1999). Cotton yield, in contrast to that of millet and sorghum, is not reduced by shading of shea nut and African mustard trees, perhaps because water capture is improved by the shading with little effect on assimilation rates in species that rely on C_3 carbon fixation (Ong and Leaky 1999). However, Payne (2000) found that reduction of vapor pressure deficit over stands of pearl millet, through shading, in combination with soil nutrient supplements could help improve pearl millet yields.

Regardless, it is clear that benefits from tree products must outweigh losses in productivity due to shading and water competition; the yields can be compensated by species matching but unlikely that this will increase total production (Kessler 1992). *Sclerocarya birrea* was found to be one of the four most preferred species in 60 farmers' fields in Northern Burkina Faso and was most often valued for food (49%), fodder (21.4%), erosion control (3.9%), domestic use (7.8%), and shade in agricultural area (2%) (Leenders et al. 2005).

A diversification of rural economic activities and a social reorganization must accompany agricultural advances (Turner and Robbins 2008). Improvements must rely on results from modeling of water and energy fluxes in natural savannas (Brümmer et al. 2008a, b, 2009; Grote et al. 2009) in order to improve the separation between natural and cultivated patches to be compatible with local, cultural, and economic tendencies (DeFries 2008; Hobbs and Cramer 2008).

15.1.3 Solution: Wireless Sensor Networks

Wireless sensor networks (WSNs) are a new generation of measurement systems with a built-in capacity to produce high temporal and spatial density measures (Szewcszyk et al. 2004; Langendoen et al. 2006; Barrenetxea et al. 2008). They are composed of multiple autonomous sensing stations, which typically operate in a self-organized manner and communicate together using low-power radio modules. Sensing stations regularly transmit data (e.g., air temperature and humidity, wind speed and direction, soil moisture) to a sink, which in turn, uses a gateway to relay the data to a remote server. Due to their capability to produce high temporal and spatial density data, WSNs have a high potential for improving environmental data acquisition and for interfacing with scientists, managers, and farmers (Martinez et al. 2004; Werner-Allen et al. 2005; Sikka et al. 2006; Selavo et al. 2007).

One of the unique features of WSN is multihop routing (Buonadonna et al. 2005; Barrenetxea et al. 2008), which, under some restrictions, allows sensing stations to be placed farther away from the sink than the communication range of the low-power radio module. In this kind of routing mechanism, data packets are forwarded along a chain of stations, from the slave station to the sink. This feature has the advantage of enabling data to be gathered over a wide area with only one single sink. The sink usually relies on the GPRS network, largely available worldwide, to transmit the collected data from the deployed stations to any computer connected to the Internet.

Use of WSN in developing countries can stimulate innovative applications that would improve environmental sustainability by providing environmental data at low costs and improving understanding of environmental processes (Kumar et al. 2007, 2008, 2009). On a larger scale, the spread of information and communication technologies (ICTs) in developing countries remains a major preoccupation of the international community since developing ICT to its full potential still faces substantial difficulties (Zhou et al. 2008; Shah et al. 2003; Ouksel et al. 2006; Campailla et al. 2001). This is due to the lack of necessary infrastructures in less-developed countries and the difficulty in adapting existing and upcoming technology to the developing countries and the challenge of effectively managing and disseminating data for applications in a resource limited environment.

Although the cell phone is a successful example of ICT spread in developing countries, the internet has encountered more difficulties. For example, according to the International Telecommunication Union (ITU) and GSM Association (GSMA), in 2007, the number of internet users was 5.5% in Africa, 14.4% in Asia, and 26.1% in Latin America when it reached 70–80% in Western Europe and the United States; for instance, Senegal reported one computer, 0.3 internet connections and 6.6 internet users per 100 habitants in 2007. The cell phone network subscriptions in 2007 reached 28.4 mobile phone subscriptions per 100 habitants in Africa, 37.6 in Asia, and 66.7 in Latin America; for instance, 97% of all Tanzanians say they can access a mobile phone, with only 20.6 subscriptions per 100 habitants in Tanzania.

Self-organization and multihop routing make WSN highly versatile, which means their use will be favored in place of older, less user-friendly technologies. Thus, they offer potential for environmental monitoring. Given the severity of potential climate change, natural habitat fragmentation by agricultural conversion, human population increase and migration, soil salinization, and erosion in seasonally dry regions, WSN can provide appropriate monitoring systems for producing high temporal and spatial dense measurements. Moreover, as the cost for building WSN gets lower, they can cover larger monitoring areas with minimal costs, which meet the application requirements of high quality and wide coverage data, in various environmental sciences.

15.1.4 Objectives

Soil moisture emerges as the crucial variable necessary to understand in order to optimize the resource partitioning between agroforestry trees and surrounding crops and thus offers scientific support to rural farmers in countries such as Burkina Faso. Rodriguez-Iturbe et al. (1999) proposed an equation for calculating daily soil as a balance between the stochastic arrival of rainfall events and the deterministic rate of soil moisture losses at a point. They average over the rooting space or the product of soil porosity and the depth of the active rooting level. Although a stochastic model of plant water interactions has been demonstrated, the challenge of upscaling to account for competition between crops and trees is significant (Katul et al. 2007). This chapter takes the first step in exploring the applicability of such a model to a mixed *Pennisetum glaucum* and *Sclerocarya birrea* agroforestry parkland.

Data for this research was collected using wireless sensing devices (Fig. 15.1), making it the first experiment of this type using the Sensorscope network of wireless sensing devices both in an African rural development context and to study the environmental heterogeneity attributed to trees in an agricultural savanna landscape. Additionally, solar panels provided all energy for this project. Valuable lessons were learned regarding the feasibility of using this technology in this context and the potential of transferring this technology to rural farmers to improve agroforestry practices in the face of climate change.

In this chapter, we will run a simple model of soil moisture model using the actual measured rainfall from the beginning to the end of the rainy season (May to October)

Fig. 15.1 Wireless sensing device, Sensorscope' used for observation in agricultural field

as the sole input for both a herbaceous, millet-dominated vegetation cover and directly under a *Sclerocarya birrea* agroforestry tree. We will then compare the predicted soil moisture with measured values distributed over the rooting depth through the end of July. Finally, we will identify discrepancies between the modeled and the measured system to guide further study. This is a preliminary analysis of data that will guide subsequent research and point the direction for agricultural outreach inquiries specifically regarding arrangement of agroforestry trees.

15.2 Methods

15.2.1 Site Description

The Singou River Basin is located in southeast Burkina Faso in the province of Kompienga (Fig. 15.2). It is home to a rare diversity and abundance of wildlife as well as particularly dense vegetation cover, which is in part due to its protection by hunting concessions and national parks and in part due to its relative inaccessibility. However, residents of areas surrounding the protected areas have been forced to intensify agriculture that has resulted in soil degradation as well as increases in the frequency and severity of flooding and droughts. Local communities are heavily

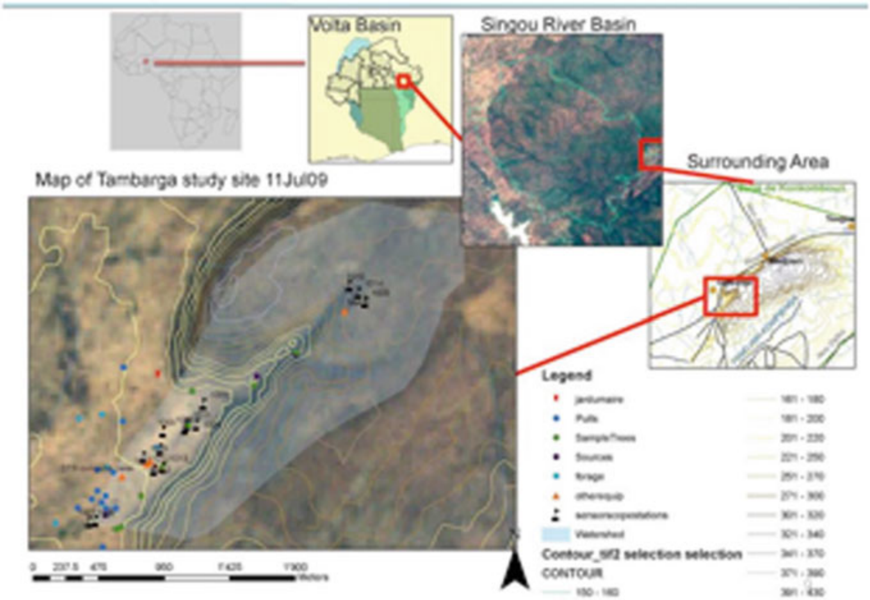

Fig. 15.2 Map of study site showing situation in basins, and equipment and sampling sites

dependent on rainfed agriculture, cultivating a mix of millet, corn, rice, sorghum, tubers in a parkland cropping system interspersed with karite or shea butter (*Vitellaria paradoxa*), Niere or African mustard (*Parkia biglobosa*), African grape (*Lannea sp*.), mango (*Magnifera indica*), Marula (*Sclerocarya birrea)*, and other fruit trees. Surrounding the farms and fallows, the landscape is a patchwork of tall grasses, meadows, interspersed large African ebony (*Khaya senegalensis*) and Baobab (*Adonsonia digitata*) trees, and shrub woodlands dominated by *Combretaceae*, wetlands, marshes, and riparian gallery forests.

This study is part of an innovative research-development project that applies recent Sensorscope technology to problems facing rural farmers in Southeastern Burkina Faso. Research themes and site choice were guided by a participatory mapping workshop held in 2008 during which residents identified current agroforestry techniques as being insufficient to buffer damages from hydrologic extremes such as droughts and floods and deforestation and reforestation with foreign species as threats to the traditional landscape.

15.2.2 Species Choice

A *Sclerocarya birrea* tree was selected to represent the large woody vegetation of the agricultural zone of the small basin based on its high prevalence and local importance (Fig. 15.3). We are currently investigating the importance of these trees to the local social economy, but in a rapid tree inventory of a representative hectare

Fig. 15.3 *Sclerocarya birrea* tree in unplanted millet field surrounded by components of wireless sensing network and solar power energy supply

of the agricultural land, six of the nine trees with a diameter at breast height (dbh) of over 10 cm were *Sclerocarya birrea*. Other species in the agricultural land include *Ficus thonningii, Magnifera indica, Piliostigma reticulatum,* and *Terminalia laxiflora*. The individual chosen is a medium tree with a dbh of 40 cm located in the agricultural upland. Comparison of large woody vegetation composition of representative 1-ha plots in agricultural and savanna land cover revealed that there are important differences between the land cover types in terms of their tree densities, species diversity, and age class distributions. Where the agricultural plot only contained nine individuals of four species, the savanna plateau site contained 254 individuals of 23 species, fewer *Sclerocarya birrea,* and all trees were considerably smaller and shrubbier. This indicates clear preference for *Sclerocarya birrea* by cultivators and is an evidence of their removal of small trees.

The relative soil moisture model that we use (Eq. 15.1) sets the change in relative soil moisture (*ds*) per time (*dt*) equal to the difference between the precipitation (*R*) and the sum of losses from canopy interception (*I*), runoff (*Q*), evapotranspiration (*E*), and leakage (*L*) or deep infiltration averaged over the rooting depth (*Zr*) and divided by the pore space (*n*). Values of soil moisture, rainfall, and interception as well as physical soil parameters were gathered during 5 months spanning the wet season.

$$nZ_r \frac{ds(t)}{dt} = R(t) - I(t) - Q[s(t), t] - E[s(t)] - L[s(t)] \tag{15.1}$$

Equation 15.1 Relative soil moisture

$$\begin{aligned}
R = h &= \begin{cases} \lambda < p \rightarrow h = 0 \\ \lambda > p \rightarrow p(h) = \dfrac{1}{\alpha} e^{\frac{-h}{\alpha}} \end{cases} \\
I &= \begin{cases} h < \Delta \rightarrow I = h \\ h > \Delta \rightarrow I = \Delta \end{cases} \\
Q &= \begin{cases} R - I < (1 - s) \cdot n \cdot Zr \rightarrow Q = (1 - s) \cdot Zr \\ R - I > (1 - s) \cdot n \cdot Zr \rightarrow Q = 0 \end{cases} \\
E &= \begin{cases} s < sw \rightarrow E = \dfrac{s \cdot E_{\max}}{sw} \\ s > sw \rightarrow E = E_{\max} \end{cases} \\
L &= K \cdot s^{2b+3}
\end{aligned} \tag{15.2}$$

Equation 15.2 Soil moisture model in detail

The relative soil moisture model that was used is based on the equation that the change in relative soil moisture (*ds*) per change in time (*dt*) is equal to the sum of canopy interception (*I*), runoff (*Q*), evapotranspiration (*E*), and leakage or deep infiltration (L) subtracted from the rainfall (R) averaged over the rooting depth (Zr) and divided by the pore space (n). This is a minimal model that can be coupled with other processes or expanded to include larger scales or higher complexity such as topography in the future. Each component of the model is calculated as shown in Eq. 15.2.

Rainfall was calculated as a marked Poisson process where time between events follows the exponential derivation, $\lambda e^{-\lambda}$, and the depth of rainfall events follows the exponential distribution of $1/\alpha e^{-h/\alpha}$. Values of λ and α were calculated for a single season, where λ is equal to the frequency of rainfall events and α is equal to the mean depth of event. Actual rainfall was recorded with a *Prećis* transduction rain gauge with a resolution of 0.1 mm placed in an open area less than 100 m from the tree of interest.

Interception prevents a part of each rainfall event from reaching the soil because the canopy intercepts it. The quantity of rainfall intercepted is complex and depends on the species, the rainfall intensity, and other seasonal and climatic variables such as wind speed or stage of leaf growth. In the past, interception has been modeled as a percent of rainfall, but this model uses a simplified threshold where Δ represents an amount under which no rain reaches the soil surface. Following the approach of Laio et al. (2001), who calculated interception when the rainfall event was greater than a value Δ*,* the amount Δ was subtracted from the depth of the event to equal throughfall, or the depth of rain reaching through the soil surface, with $\Delta = 2$ mm for (trees) and $\Delta = 0.5$ mm for grasses (millet). Alternatively, we considered the method of Samba et al. (2001) who found interception to be 9–22% depending on distance from tree (0.5–1 of the radius) in the case of *Cordyla pinatta*. They fitted interception to an exponential function equal to 1.76 times event depth to a power of 0.2971.

Runoff was taken into account when throughfall was in excess of the storage capacity. The storage capacity was calculated as the soil moisture subtracted from one and multiplied by the porosity multiplied by the rooting depth. When throughfall was greater than this storage capacity, then the runoff was calculated to be the difference between them. Leakage, or the amount of water that drains from the soil to the depth of the active roots, was calculated as the rate of saturated leakage (K), which varies according to soil texture, multiplied by the soil moisture to a power of c, where $c = 2b + 3$, and b is coefficient that is strongly related to soil texture (Clapp and Hornberger 1978).

Evapotranspiration was considered equal to soil moisture (s) multiplied by maximum evaporation (*Emax*) over the point of onset of plant water stress (*sw*) until s equaled *sw*; thereafter it was considered to be equal to *Emax*, following the method of Federer (1979). *Emax* was calculated from evaporation measurements calculated from eddy covariance technique using vertical wind speed measured with a Campbell sonic anemometer and fluctuations in water vapor concentration measured with a Kipp and Zonar Li-cor gas analyzer less than 100 m from the tree of interest in the agricultural field.

The relative soil moisture is the percent of the volumetric water content over the porosity, or in other words the volume of water in the soil over the sum of the

Table 15.1 Vegetation characteristics used in two scenarios

Scenario	Vegetation	Infiltration threshold	Rooting depth	Wilting point	Maximum evapotranspiration
		Δ (mm)	Zn (mm)	sw	Emax (mm/day)
1	Millet (*Pennisetum glaucum*)	0.55	1,400	0.12	3.4752
2	Marula (*Sclerocarya birrea*)	2	3,000	0.12	3.4752
Ref:		Laio et al. (2001)	Sivakumar and Salaam (1994), Smith et al. (1997)	Ong and Leaky (1999)	Measured

Table 15.2 Soil characteristics used in two scenarios

Dominant soil texture	Pore size distribution index	Porosity	Hygroscopic point	Saturated leakage
	b	n	s(1)	K (mm/day)
Silty loam	4.977	0.39	0.15	622.08
Bunasol (personal communication) 2008	Fernandez-Illescas et al. (2001)	Sampled	Initial measured	Clapp and Hornberger (1978)

volume of air and water. This model is only concerned with the soil in the active root space and averages over that depth. The values of soil moisture ranged between perfectly dry soil (0) and saturated soil (1). Initial soil moisture was estimated at the hygroscopic point, or as close to zero as possible since the model simulation began in January, in the dry season. Calculation was done at a time step of 1 day. All calculations were made in millimeters. Tables 15.1 and 15.2 show the values of all parameters used for the model.

Volumetric water content of soil was measured with the Decagon Devices EC-TM soil moisture and temperature sensor (Fig. 15.4), that measures the volumetric water content between 0 and 1 m^3/m^3 with a resolution of 0.0008 m^3/m^3. Sensors were placed along two axes running north and east from the base of the tree at radial distance of 0, 2, 5, and 7 m and depths of 15, 30, and 70 m following a general Doehlert design. Fifteen meters from the tree, sensors were installed in an agricultural field at 15 and 30 cm depth at a single point. For the purpose of this analysis, measurements at the depths are averaged for each point. Sensors were attached to a wireless sensing network of Sensorscope stations. In addition to automatic sensing, soil samples were taken for analysis of volumetric water content by drying in an oven at 105°C for 24 h. The volumetric water content was calculated by subtracting the dry weight from the wet weight and dividing by the dry weight. Soil porosity was calculated by weighing samples of 100 cm cubed after drying in a drying oven at 105°C for 24 h. The weight over the volume or apparent density was divided by 2.65 to obtain the soil porosity. These values were used to verify automatic sensor values.

Fig. 15.4 Decagon Devices EC-TM soil moisture sensor installed under tree

15.3 Results

Total rainfall for the 2009 season was 788 mm which is below the average for the nearest long-term data record at Pama, 60 km away, from 1978 to 2007 (867.2 mm, Meteo Burkina Faso). Modeled rainfall did not demonstrate the same level of variation and irregularity that the actual rainfall did, although the original values for frequency, 0.64495/day, and mean, 9.0575, were used (Figs. 15.5 and 15.6). For this reason, the subsequent model was calculated in response to actual rainfall.

As shown in Tables 15.1 and 15.2, the only changes between the scenarios were interception and rooting depth; however, we see that even these changes affect the sensitivity of the system. The leakage in particular is much higher in the case of millet, and the storage capacity is much higher for the Marula tree.

The final plots in Figs. 15.5 and 15.6 compare the actual response to precipitation and the modeled response. We see that in both cases, the predicted response is a good estimate until July when modelled soil moisture content continues to rise, whereas actual soil moisture decays. At the tree, we focus on the response at a midpoint of the rooting depth, 30 cm. We see that position in relation to the trunk changes the response considerably. The stemflow, flowing at the base of the tree, is a much larger input to the system than the canopy infiltration that we accounted for in this model. Counterintuitively, the values at the edge of the canopy, at 7 m, also are more important than the midcanopy (5 m), which is even, less than the near canopy (2 m). In the millet field, we observe that deeper soils are wetter until July when shallow soils respond much more quickly to the rain event.

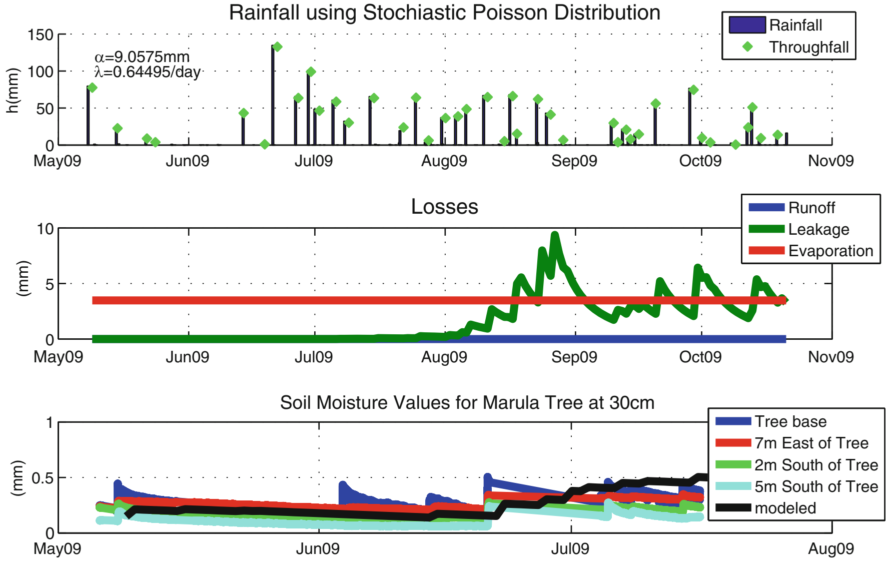

Fig. 15.5 Comparison of inputs, losses, and final soil moisture under *Sclerocarya birrea*

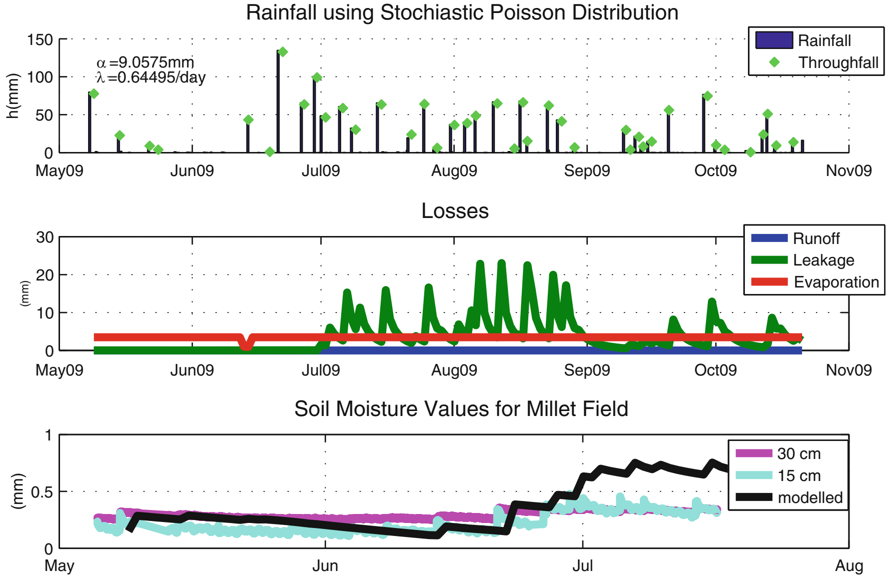

Fig. 15.6 Comparison of inputs, losses, and final soil moisture under *Pennisetum glaucum*

15.4 Discussion

The simplistic soil moisture model correctly approximated a part of the response of soil moisture to rainfall; however, it is inadequate as time continues. From examination of actual data, it is apparent that there is considerable spatial variation based on the direction and distance from the trunk because of the combined influence of water routing by the branches and trunk, exposure to direct sunlight, and possible slope effects. The model of soil moisture in the open field similarly gives an average response for soil moisture that it is approximately correct until late June. What happened around the transition from June to July that the model fails to include?

In both cases, the runoff component is zero for the entirety of the modeled time; however, there was clear evidence of runoff in both cases in the field following rain events, particularly as the season progressed. In our model, runoff is formed when the amount of throughfall received exceeds storage capacity. According to our current examination, this never occurred, but perhaps it did occur at different spatial parts of the soil, explaining the discrepancy between model and real values. The upper layer of soil may have been completely saturated, generating runoff, even if the vertically averaged storage capacity was not full. When rainfall intensity is high, it exceeds the infiltration capacity of the soil, pools and generates runoff (Brutsaert 2005). The infiltration capacity of the soil needs to be measured at different depths to improve estimations from the literature.

We see the importance of position under the canopy in the subtree moisture response (Fig. 15.5). Settin et al. (2007) found that the spatial averages over a large basin of the proposed analytical model do describe the soil moisture dynamics when seasonal dynamics are included. According to their work, improved parameterization of our soil moisture model could be made if we average all values spatially. For example, we have made estimations of wilting point and rooting depths based on literature for other species; however, this is an opportunity to solve the equation for these parameters.

Alternatively, we may need to further describe the spatial heterogeneity. Katul et al. (1997) proposed a linearized Taylor series to explain the vertical variation in soil moisture loss due to root water uptake in a growth chamber. Their model will allow for the inclusion of diurnal recharge due to the nighttime slow of transpiration. Developing our model so that it accounts for root density variation and benefits from sap flux measurements may help reduce the observed error.

Isham et al. (2005) proposed a method to account for the variability in space and time of the basic soil moisture model by breaking the model space into cylindrical cells. For our purpose, their strategy might allow us to account for the variation in factors such as radial direction and distance from tree base; however, addition of throughfall must be calculated in relation to the canopy architecture. Baldocchi et al. (2004) found in their examination of oak savannas that it is essential to account for variations in evaporative demand over the savanna space. Our current model used evaporation from a nearby eddy covariance tower, but we should explore methods to measure the latent heat flux at smaller scales and particularly to compare between and under canopies.

Caylor et al. (2006) proposed representing savanna heterogeneity as an overlapping network of leaf and root canopies. In this way, they describe the spatial variability of soil moisture at a larger scale. However, there is no clear account for interaction between woody and herbaceous vegetation in their case of a natural savanna using a Poisson distribution to estimate the spatial arrangement of canopies in a Kalahari transect. In 2005, Caylor et al. examined the interaction between trees and grasses using a coupled soil moisture and energy balance method for the Kalahari Desert (Caylor et al. 2005). They compare under canopy and between canopy levels of soil moisture in terms of the quantity of water stress on the vegetation. They found that areas between canopies experienced higher levels of stress than under canopies, and in this way the trees shielded the water stress of understory vegetation in periods of drying. This is the opposite of what we found over the rainy season; however, it might bare more similarity to what we will find as we continue our work into the dry season. We found that the soil moisture was less under canopies, where there is presumably more root uptake.

Our preliminary results are not conclusive enough to make a strong recommendation to rural farmers in regards to managing soil moisture dynamics through woody vegetation. However, our data does show that water is more available in the between canopy spaces, as Ong et al. (2002) warned. Even so, there were still generous levels of soil moisture under canopy, particularly at the base of the trunk. The high level of soil moisture that our model produced in contrast to the actual measured soil moisture shows the potential soil moisture if runoff was reduced to zero. Encouragement of pooling through artificial barriers is the most effective way to trap this moisture in both the open and subcanopy space. Our data suggests the importance of incorporating the spatial heterogeneity of subcanopy into planting techniques. We thus recommend exploration of crop varieties that correspond to the moisture and light regimes under canopies, coupled with half-moon techniques of stone lines to trap stemflow at the base of the tree trunk.

The soil moisture data used for this analysis was collected using soil moisture probes distributed throughout the rooting area of an agroforestry tree. These data were part of a wireless sensing network of Sensorscope stations. This research would not have been possible without multiplexing a large number of sensors on a single station, arranged around a tree. Over the 3-month period, these stations required very little maintenance; however, once the rainy season progressed into August, the combination of electricity and humidity rendered some of the components ineffective. Improvements have been made to prevent damage in future seasons. Solar energy provided all of the power for these stations without any problem, even over the course of the rainy season. Solar energy is well adapted to dry-land ecosystems as a minimal amount of daily solar radiation can be guaranteed.

15.5 Conclusions

This chapter made an important first step in applying a simplistic soil moisture model to the *Sclerocarya birrea* agricultural parkland in Burkina Faso. Further work needs to be examined to account for rainfall intensity and the subsequent runoff levels. Spatial heterogeneity under canopy space should be examined in more detail in particular in relation to root and canopy architecture and variations in evaporative demand. Our data suggests some preliminary agroforestry solutions that can optimize water use in this ecosystem such as under canopy planting of crops with lower light and water requirements and stone half-moon placement to encourage runoff infiltration particularly from stemflow.

This research represents an important first use of wireless sensing networks for environmental management in small-scale rural farms in West Africa. Data was successfully collected over the course of a rainy season. Subsequent work will make this technology more accessible to the farmers and community leaders themselves. The preliminary conclusions of this research already demonstrate the usefulness of this technology to find agroforestry solutions to the hydrologic problems presented by climate change for rural farmers.

References

Baldocchi, D. D., Xu, L., & Kang, N. (2004). How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savannah and an annual grassland. *Agricultural and Forest Meteorology, 123*(1–2), 13–19.

Barrenetxea, G., Ingelrest, F., Schaefer, G., & Vetterli, M. (2008). SensorScope: The hitchhiker's guide to successful wireless sensor network deployment. *Proceedings of the 6th ACM Conference on Embedded Networked Sensors Systems (SenSys 08)*, Raleigh, NC, USA.

Brümmer, C., Brüggermann, N., Butterbach-Bahl, K., Falk, U., Szarzynski, J., Vielhauer, K., Wassmann, R., & Papen, H. (2008a). Soil-atmosphere exchange of N2O and NO in near-natural savannah and agricultural land in Burkina Faso. *Ecosystems, 11*(4), 582–600.

Brümmer, C., Falk, U., Papen, H., Szarzynski, J., Wassmann, R., & Brüggermann, N. (2008b). Diurnal, seasonal, and interannual variation in carbon dioxide and energy exchanges in shrub savannah in Burkina Faso. *Journal of Geophysical Research, 113*(G02030), 1–11.

Brümmer, C., Papen, H., Wassmann, R., & Brüggermann, N. (2009). Fluxes of CH4 and CO2 from soil and termite mounds in south Sudanian savannah of Burkina Faso. *Global Biochemical Cycles, 23*(1), 1–13.

Brutsaert, W. (2005). *Hydrology: An introduction*. Cambridge: Cambridge University Press.

Buonadonna, P., Gay, D., Hellerstein, J., Hong, W., & Madden, S. (2005). TASK: Sensor network in a box. *Proceedings of the Second IEEE European Workshop on Wireless Sensor Networks and Applications*. doi:10.1109/EWSN.2005.1462005.

Campailla, A., Chaki, S., Clarke, E., Jha, S., & Veith, H. (2001). Efficient filtering in publish-subscribe systems using binary decision diagrams. *Proceedings of the 23rd International Conference on Software Engineering (ICSE '01)*, Toronto, pp. 443–452.

Cannell, M. G. R., Noordwijk, M. V., & Ong, C. K. (1996). The central agroforestry hypothesis: The trees must acquire resources that the crop would not otherwise acquire. *Agroforestry Systems, 34*(1), 27–31.

Caylor, K., Shugart, H. H., & Rodriguez-Iturbe, I. (2005). Tree canopy effects on simulated water stress in Southern African savannas. *Ecosystems, 8*(1), 17–32.

Caylor, K., D'Odorico, P., & Rodriguez-Iturbe, I. (2006). On the ecohydrology of structurally heterogeneous semiarid landscapes. *Water Resources Research, 42*(7), 1–13.

Clapp, R. B., & Hornberger, G. M. (1978). Empirical equations for some soil hydraulic properties. *Water Resources Research, 14*(4), 601–604.

DeFries, R. (2008). Terrestrial vegetation in the coupled human-earth system: Contributions of remote sensing. *Annual Review of Environmental Resources, 33*, 369–390.

Delmas, R. A., Mraenco, A., Tathy, J. P., Cros, B., & Baudet, J. G. R. (1991). Sources and sinks of methane in the African savannah. *Journal of Geophysical Research – Atmosphere, 96*(D4), 7287–7299.

Donner, L. J., & Large, W. G. (2008). Climate modeling. *Annual Review of Environmental Resources, 33*, 1–17.

Downing, T. E., Ringius, L., Hulme, M., & Waughray, D. (1997). Adapting to climate change in Africa. *Mitigation and Adaption Strategies for Global Change, 2*(1), 19–44.

Falkenmark, M., & Rockstrom, J. (2006). The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of Water Resources Planning and Management, 132*(3), 129–132.

Federer, C. A. (1979). A soil-plant-atmosphere model for transpiration and availability of soil water. *Water Resources Research, 15*(3), 555–562.

Fernandez-Illescas, C. P., Porporato, A., Laio, F., & Rodriguez-Iturbe, I. (2001). The ecohydrological role of soil texture in a water-limited ecosystem. *Water Resources Research, 37*(12), 2863–2872.

Fries, J., & Heermans, J. (1992). Natural forest management in semi-arid Africa: Status and research needs. *Unasylva, 43*(168), 9–15.

Furley, P. (2004). Tropical savannas. *Progress in Physical Geography, 28*, 581–598.

Griffith, A. L. (1961). Dry woodlands of Africa South of the Sahara. *Unasylva, 15*(1).

Grote, R., Lehmann, E., Brümmer, C., Brüggemmann, N., Szarzynski, J., & Kunstmann, H. (2009). Modeling and observation of biosphere-atmosphere interactions in natural savannah in Burkina Faso, West Africa. *Physics and Chemistry of the Earth, 34*(4–5), 251–260.

Hobbs, R. J., & Cramer, V. A. (2008). Restoration ecology: Interventionist approaches for restoring and maintaining ecosystem function in the face of rapid environmental changes. *Annual Review of Environmental Resources, 33*(1), 39–61.

Hulme, M., Doherty, R., Ngara, T., New, M., & Lister, D. (2000). African climate change 1900–2100. *Climate Research, 17*(2), 145–168.

Isham, V., Cox, D. R., Rodriguez-Iturbe, I., Porporato, A., & Manfreda, S. (2005). Representation of space-time variability of soil moisture. *Proceedings of the Royal Society A, 461*(2064), 4035–4055.

Jonsson, K., Ong, C. K., & Odongo, J. C. W. (1999). Influence of scattered néré and karité trees on microclimate, soil fertility, and millet yield in Burkina Faso. *Exploratory Agriculture, 35*(1), 39–53.

Kallis, G. (2008). Droughts. *Annual Review of Environmental Resources, 33*, 85–118.

Katul, G., Todd, P., Pataki, D., Kabala, Z., & Oren, R. (1997). Soil water depletion by oak trees and the influence of root water uptake on the moisture content spatial statistics. *Water Resources Research, 33*(4), 611–623.

Katul, G., Porporato, A., & Oren, R. (2007). Stochastic dynamics of plant-water interactions. *Annual Review of Ecology, Evolution, and Systematics, 38*, 767–791.

Kessler, J. (1992). The influence of karité (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) trees on sorghum production in Burkina Faso. *Agroforestry Systems, 17*(2), 97–118.

Kumar, A., Rajput, N., Chakraborty, D., Agarwal, S. K., & Nanavati, A. A. (2007). WWTW: The world wide telecom web. *Proceedings Workshop on Networked Systems for Developing Regions*. doi:10.1145/1326571.1326582.

Kumar, A., Rajput, N., Agarwal, S., Chakraborty, D., & Nanavati, A. A. (2008). Organizing the unorganized – employing IT to empower the under-privileged. *Proceedings of the 17th International Conference on the World Wide Web*, New York. doi: 10.1145/1367497.1367623.

Kumar, A., Chakraborty, D., Chauhan, H., Agarwal, S., & Rajput, N. (2009). FOLKSOMAPS – Towards community driven intelligent maps for developing regions. *Proceedings of the IEEE/ACM International Conference on Information and Communication Technologies and Development (ICTD)*. doi:10.1109/ICTD.2009.5426701.

Laio, F., Poroporato, A., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress II. Probabilistic soil moisture dynamics. *Advances in Water Resources, 24*(7), 707–723.

Langendoen, K., Baggio, A., & Visser, O. (2006). Murphy loves potatoes: Experiences from a pilot sensor network deployment in precision agriculture. *Proceedings of the 20th IEEE International Parallel and Distributed Processing Symposium*, Rhodes Island. doi: 10.1109/IPDPS.2006.1639412.

Leenders, J. K., Visser, S. M., & Stroosnijder, L. (2005). Farmers' perceptions of the role of scattered vegetation in wind erosion control on arable land in Burkina Faso. *Land Degradation and Development, 16*(4), 327–337.

Mahe, G., Olivry, J. C., & Servat, E. (2005). *Sensitivity of West-African rivers to climatic and environmental changes: Extremes and paradoxes*. Wallingford: IAHS Press.

Martinez, K., Hart, J., & Ong, R. (2004). Environmental sensor networks. *IEEE Computer Society, 37*, 50–56.

Miles, L., Newton, A. C., DeFries, R. S., Ravilious, C., May, I., Blyth, S., Kaspos, V., & Gordon, J. E. (2006). A global overview of the conservation status of tropical dry forests. *Journal of Biogeography, 33*(3), 491–505.

Murphy, P. G., & Lugo, A. E. (1986). Ecology of tropical dry forest. *Annual Review of Ecology and Systematics*, *10*(1), 17, 67–88.

Neumann, K., Kahlheber, S., & Uebel, D. (1998). Remains of woody plants from Saouga, a medieval West African village. *Vegetation History and Archaeobotany, 7*(2), 57–77.

Ong, C. K., & Leaky, R. R. B. (1999). Why tree-crop interactions in agroforestry appear at odds with tree-grass interactions in tropical savannahs. *Agroforestry Systems, 45*(1–3), 109–129.

Ong, C. K., Wilson, J., Deans, J. D., Mulayta, J., Raussen, T., & Wajja-Musukwe, N. (2002). Tree-crop interactions: Manipulation of water use and root function. *Agricultural Water Management, 53*(1–3), 171–186.

Ouksel, A. M., Jurca, O., Podnar, I., & Aberer, K. (2006). Efficient probabilistic subsumption checking for content-based publish/subscribe systems. *Proceedings 7th International Middleware Conference*, Melbourne, pp. 121–140.

Payne, W. A. (2000). Optimizing crop water use in sparse stands of pearl millet. *Agronomy Journal, 92*(5), 808–814.

Richards, P. (1985). *Indigenous agricultural revolution: Ecology and food production in West Africa*. London: Hutchinson.

Rockstrom, J., & Falkenmark, M. (2000). Semiarid crop production from a hydrological perspective: Gap between potential and actual yields. *Critical Reviews in Plant Sciences, 19*(4), 319–346.

Rodriguez-Iturbe, I., Porporato, A., Ridolfi, L., Isham, V., & Cox, D. R. (1999). Probabilistic modeling of water balance at a point: The role of climate, soil and vegetation. *Proceedings of the Royal Society Academy of London Series A Mathematical Physical and Engineering Sciences, 455*(1990), 3789–3805.

Samba, S. A. N. S., Camire, C., & Margolis, H. A. (2001). Allometry and rainfall interception *of Cordyla pinnata* in a semi-arid agroforestry parkland, Senegal. *Forest Ecology and Management, 154*(1–2), 277–288.

Savadogo, P., Sawadogo, L., & Tiveau, D. (2007). Effects of grazing intensity and prescribed fire on soil physical and hydrological properties and pasture yield in the savannah woodlands of Burkina Faso. *Agriculture, Ecosystems and Environment, 118*(1–4), 80–92.

Schuol, J., Abbaspour, K. C., Yang, H., Srinivasan, R., & Zehnder, A. J. B. (2008). Modeling blue and green water availability in Africa. *Water Resources Research, 44*(7), 1–18.

Selavo, L., Wood, A., Cao, Q., Sookoor, T., Liu, H., Srinivasan, A., Wu, Y., Kang, W., Stankovic, J., Young, D., & Porter, J. (2007). LUSTER: Wireless sensor network for environmental research. *Proceedings of the 5th ACM International Conference on Embedded Networked Sensor Systems*, Sydney. doi: 10.1145/1322263.1322274.

Settin, T., Botter, G., Rodriguez-Iturbe, I., & Rinaldo, A. (2007). Numerical studies on soil moisture distributions in heterogeneous catchments. *Water Resources Research, 43*(5), 1–13.

Shah, S., Dharmarajan, S., & Ramamritham, K. (2003). An efficient and resilient approach to filtering and disseminating streaming data. *Proceedings of the 29th International Conference on Very Large Data Bases*, Berlin, pp. 57–68.

Sikka, P., Corke, P., Valencia, P., Crossman, C., Swain, D., & Bishop-Hurley, G. (2006). Wireless ad hoc sensor and actuator networks on the farm. *Proceedings of the 5th ACM/IEEE International Conference on Information Processing in Sensor Networks*, Nashville. doi: 10.1145/1127777.1127852.

Sivakumar, M. V. K., & Salaam, S. A. (1994). A wet excavation method for root/shoot studies of pearl millet on the sandy soils of the Sahel. *Experimental Agriculture, 30*(3), 329–336.

Smith, D. M., Jarvis, P. G., & Odongo, J. C. W. (1997). Sources of water used by trees and millet in Sahelian windbreak systems. *Journal of Hydrology, 198*(1–4), 140–153.

Szewcszyk, R., Mainwaring, A., Polastre, J., Anderson, J., & Culler, D. (2004). Lessons from a sensor network expedition. *1st IEEE European Workshop on Wireless Sensor Networks and Applications*, Berlin, 2920, pp. 307–322.

Thomas, R. J. (2008). Opportunities to reduce the vulnerability of dryland farmers in Central and West Asia and North Africa to climate change. *Agriculture, Ecosystems and Environment, 126*(1–2), 36–45.

Turner, B. L., & Robbins, P. (2008). Land-changes science and political ecology: Similarities, differences, and implications for sustainability science. *Annual Review of Environmental Resources, 33*, 295–316.

Wallace, J. S., & Gregory, P. J. (2002). Water resources and their use in food production systems. *Aquatic Sciences, 64*(4), 363–375.

Werner-Allen, G., Johnson, J., Ruiz, M., Welsh, M., & Lees, J. (2005). Monitoring volcanic eruptions with a wireless sensor network. *Proceedings of the 2nd IEEE European Workshop on Wireless Sensor Networks and Applications*, Istanbul. doi: 10.1109/EWSN.2005.1462003.

Williams, M. (2008). A new look at global forest histories of land clearing. *Annual Review of Environmental Resources, 33*(1), 245–367.

Wittig, R., Konig, K., Schmidt, M., & Szarzynski, J. (2007). A study of climate change and anthropogenic impacts in West Africa. *Environmental Science and Pollution Research, 14*(3), 182–189.

Zheng, X., & Eltahir, E. (1998). The role of vegetation in the dynamics of West African monsoons. *Journal of Climate, 11*, 2078–2096.

Zhou, Y., Ooi, B. C., & Tan, K. L. (2008). Disseminating streaming data in a dynamic environment: An adaptive and cost-based approach. *The Very Large Data Bases Journal, 17*(6), 1465–1483.